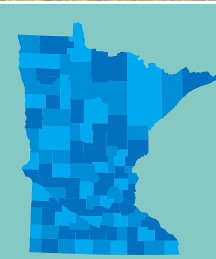
Stormwater Research

January 2025

Roadside Swale Performance

A study of field performance, modeling, and design criteria for roadside swales to meet runoff volume reduction goals

MINNESOTA POLLUTION CONTROL AGENCY



Contributions and Acknowledgements

Report Authored by: Joanne Boettcher, PE, MPCA Stormwater Research Liaison
Original Project Lead: David Fairbairn, PhD, (former) MPCA Stormwater Research Scientist

The field set-up and study were a collaboration between MPCA and MNDOT. Support with data processing, field planning and set-up, modeling, and review were provided via contracts with Barr Engineering, Wenck Associates (now Stantec), and SRF Consulting. Additional analyses were conducted by the report author to facilitate final development of the project and report.

Additional graphics development support from Andre Scott and Aaron Hinz.

Many thanks to the multiple entities and individuals who served on the project Advisory Team and in review of the final report.

Contents

Executive Summary

Swales are vegetated channels or ditches commonly used along roadsides to collect, treat, and convey stormwater. Swales can provide water quality and quantity treatment through several mechanisms including filtration, infiltration, evapotranspiration, and biochemical processes. The objectives of this study were to: 1) quantify the volume removal (referred to as abstraction, which includes infiltration, evapotranspiration, and storage) occurring in road-side swales using a water budget analysis and 2) model abstraction at the field sites using three models and compare the model and field study results. A later goal developed by the report author was to 3) assess the study swales against critical design requirements and recommendations.

Objective 1: Quantify Swale Abstraction

Five swale sites were studied over a multi-year period by isolating a section of the swale using an upstream and downstream weir, measuring water level and precipitation, and applying analysis methods including a simplified water budget application. The simplified water budget, which assumed ground water was negligible, allowed for runoff and abstraction (combined infiltration, evapotranspiration, and storage) to be deduced from the water level and precipitation data.

Nine seasonal, site-year data sets were collected and analyzed to develop runoff and abstraction ratios on a seasonal and rainfall-runoff event basis. Generally, confidence in the accuracy of the data was low. The seasonal runoff ratios varied from -527% to 233%, four of the nine runoff ratios were outside of the feasible range of 0-100%. The two data sets with the highest estimated confidence showed 99% and 87% seasonal runoff ratios, corresponding 1% and 13% seasonal abstraction ratios. The rainfall-runoff event-based runoff ratios for all sites ranged from -1,023% to 1,962%. The rainfall-runoff abstraction rates for the highest estimated confidence data sets were between -0.02 to 0.06 inch per hour, analyzed at the event time scale.

The data and/or assumptions associated with this water budget analysis generally appear problematic. Based on characteristics of the data and reports from the original project team, the factors suspected of creating the largest problems in the study are groundwater discharge, seepage around the weirs, inaccurate watershed size estimates, and instrument/measurement errors. A high water table was likely contributing groundwater discharge to many of the sites, invalidating a key assumption of the simplified water budget application. Despite a high amount of rigor by the original project team, quantifying abstraction in roadside swales - with confidence - was not successful in this project.

Objective 2: Model Abstraction and Comparison to Field Results

Three models, the MPCA MIDS calculator, the UMN Dry Swale Calculator, and XPSWMM were used to model the Site 3 and 4 study swales because these two sites each had a higher confidence site-year data set. Model results were transformed into (as close as possible) equivalent terms, and the results compared to the field results.

Modeled and transformed abstraction ratios ranged from 92% to 13% at Site 3 and from 95% to 7% at Site 4. However, comparison amongst the various model outputs and comparison of these to the field data should be done cautiously because: 1) the field data were suspect and may not be useful for comparisons, 2) neither the MPCA nor UMN tool accommodate HSG D soils (and Sites 1-4 were later found to have HSG D soils), 3) XPSWMM modeling assumed HSG B infiltration rate soils and did not account for high groundwater, and 4) while the outputs were transformed to equivalent units, assumptions were necessary to make these transformations and the results may not be categorically comparable.

Of key interest, the MIDS calculator results and the UMN calculator results were compared after transforming the calculator outputs to equivalent terms. While the sites could not be modeled as HSG D soils due to limitations in both of the calculators, both sites 3 and 4 were modeled using the same soil infiltration rates in both of the calculators. In this way, the results are comparable. At both sites 3 and 4, the UMN calculator estimated substantially more abstraction (39% and 36%, respectively) than the MIDS calculator (13% and 7%, respectively). Of particular concern, the UMN calculator does not consider the upstream contributing area or the swale geometry. A detailed review of the methods and robustness of these calculators was beyond the scope of this study, however.

Objective 3: Assess Study Swales for Conformity to Design Criteria

Since quantification of swale abstraction (objective 1) did not yield high confidence results, soils data was reviewed in detail to shed light on potential issues with the project, which evolved into objective 3. Five critical design criteria were reviewed, three of which are related to soils and required by the CSW Permit.

Soils review incorporated desktop analysis, soil profile observations, and Modified Phillip-Dunne (MPD) measurements. Sites 1-4 were generally Hydrologic Soil Group (HSG) C soils and Site 5 was HSG B soils as shown in the NRCS SSURGO database. In desktop imagery reviews, surface water table features were observed near sites 1-4. Field soil observations revealed a range of soil types, disturbed soils, and saturated soil conditions, resulting in Sites 1-4 being classified as HSG D soils. This limited review suggests that areas near observable water table or wetland type features (and without large changes in elevation or other extenuating circumstances) should be field-investigated as likely HSG D soils. Likewise, areas that were impacted during historical construction will likely have compacted conditions, which could result in impermeable soil layers and a HSG D classification.

Using only surface MPD measurements to estimate k_{sat} can result in the incorrect assessment that the soils are a more transmissive HSG. Once the full definition of HSGs was applied to the soil profile observations, the soils were found to be less transmissive. Based on the high water table (assessed as periodically/seasonally saturated soils), Sites 1-4 were classified as HSG D soils (or dual soil groups). The more transmissive surface k_{sat} values likely reflect the macropores, root channels, and other more transmissive conditions in the topsoil compared to the underlying subsoils and particularly, the least transmissive layer.

Overall, Sites 1-4 did not meet several of the identified design criteria. A key take-away being that accurate characterization of soil in (proposed) infiltration areas is critical from both the experimental perspective of this project, specifically, and in the effectiveness of infiltration projects, generally. The soil types, structure (condition/disturbance), and high water table likely hindered infiltration at these sites. Other critical design criteria, the contributing area and ratio of pervious and impervious area, were also exceeded at some of the project sites. Infiltration areas that are inundated by runoff from excessively large contributing areas will inherently have limited capacity to treat the target runoff. As such, these criteria may warrant a closer review when designing infiltration practices for water quality treatment and volume reduction goals.

Introduction

Swales are vegetated channels or ditches commonly used along roadsides to collect, treat, and convey stormwater. Swales can provide water quality and quantity treatment through several mechanisms including filtration, infiltration, evapotranspiration, and biochemical processes. Figure 1 illustrates the physical features and treatment processes of a swale.

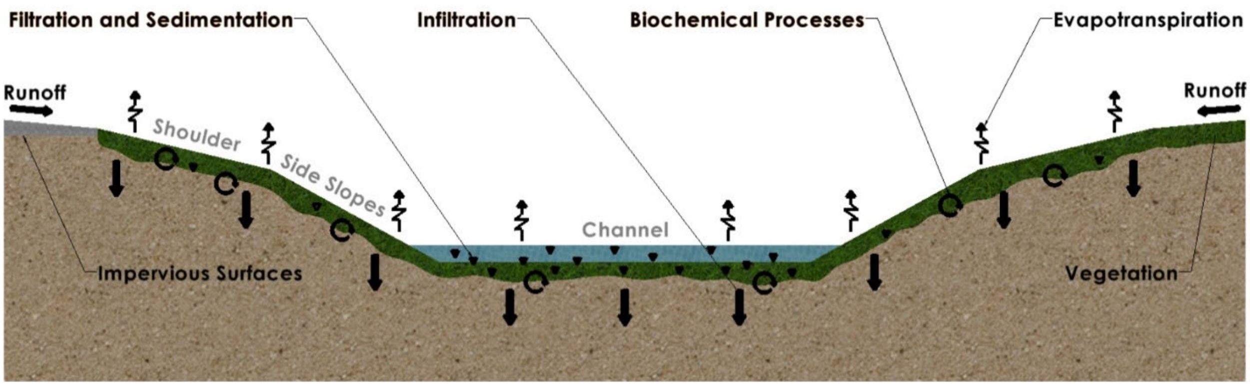


Figure 1: This cross-sectional view of a swale shows a swale's physical features and treatment mechanisms. The physical features of a swale include the side slopes, channel, vegetation, and underlying soil. Treatment mechanisms include infiltration, evapotranspiration, settling, filtration, and bio-chemical process. Image adapted from NC State Extension, 2020.

Several factors affect a swale's ability to treat water quality and quantity including the underlying soil type and condition, depth to the water table or impermeable layers, channel slope and water retention time, watershed size, runoff and pollutant loading, and retention features including impoundments and vegetation. As such, the design of a swale can affect treatment processes by incorporating specific components such as check dams, engineered soils, underdrains, or specially selected vegetation.

Minnesota Pollution Control Agency's (MPCA) National Pollutant Discharge Elimination System/State Disposal System (NPDES/SDS) Construction Stormwater General Permit (CSW Permit) requires projects that create one or more acres of new impervious area to construct a permanent stormwater treatment system to treat a specified water quality treatment volume. MPCA developed the Minimum Impact Design Standards (MIDS) calculator to assist designers in calculating the necessary water quality treatment volume and the amount of treatment in a designed treatment system, including swales.

Minnesota Department of Transportation (MNDOT) installs swales alongside the hundreds of miles of roads it builds annually. MNDOT contracted the University of Minnesota (UMN) to study swale design and effectiveness. Outcomes of the projects included two reports: Assessing and Improving Pollution Prevention by Swales and Enhancement and Application of Minnesota Dry Swale Calculator (UMN Calculator).

MNDOT requested approval from the MPCA to use the Minnesota Dry Swale Calculator to calculate volume reductions rather than the MIDS Calculator. However, MPCA was concerned that assumptions in the Minnesota Dry Swale Calculator were leading to excessive performance estimates, as the UMN Calculator tends to estimate larger volume reductions than the MIDS calculator. Therefore, MPCA and MNDOT agreed to partner on a study to quantify the water volume removal of swales under field conditions, the impetus of this project.

The project was designed as a multi-year field study with additional time for data processing and analysis. The project was further extended due to complications, staff changes, and the COVID-19 pandemic. Project conception, planning, data collection, and initial data processing and analysis were

conducted by the original project team from 2016 to 2021, at which time the MPCA Stormwater Research Scientist left the MPCA. Additional analyses were completed, and this report drafted by the MPCA Stormwater Research Liaison in 2023-2024. Since the author was not involved in the project design, data collection, and parts of the analysis, this report was provided to the former project team and partners for review and their comments incorporated as appropriate.

Project Objectives

Based on the original project intent, the objectives of this study were to: 1) quantify the water volume removal (i.e. abstraction) occurring in road-side swales under field/naturalized conditions over varying time scales using the water budget and 2) model volume reductions using the UMN Dry Swale Calculator, the MPCA MIDS Calculator, and XPSWMM and compare the model results to the field observations. A later goal developed by the report author was to 3) assess the study swales against the CSW Permit requirements and design recommendations from the MN Stormwater Manual.

Site Selection and Characterization

Five swales (Figure 2) were selected for the study based on proximity to the Twin Cities metro area, accessibility, safety, feasibility to obtain necessary data, being a common swale configuration, and representation of a range of soil types. Sites 1 and 2 were located at the MnROAD research facility adjacent Interstate Highway 94 near Albertville. Site 3 was located along U.S. Trunk Highway 212 near Chaska. Site 4 was located along U.S. Trunk Highway 8 near Shafer. Site 5 was located at the entrance ramp to the St. Croix Weigh Station on Interstate Highway 94 near Afton and divided into two subsites: 5B (beehives) and 5S (swales).

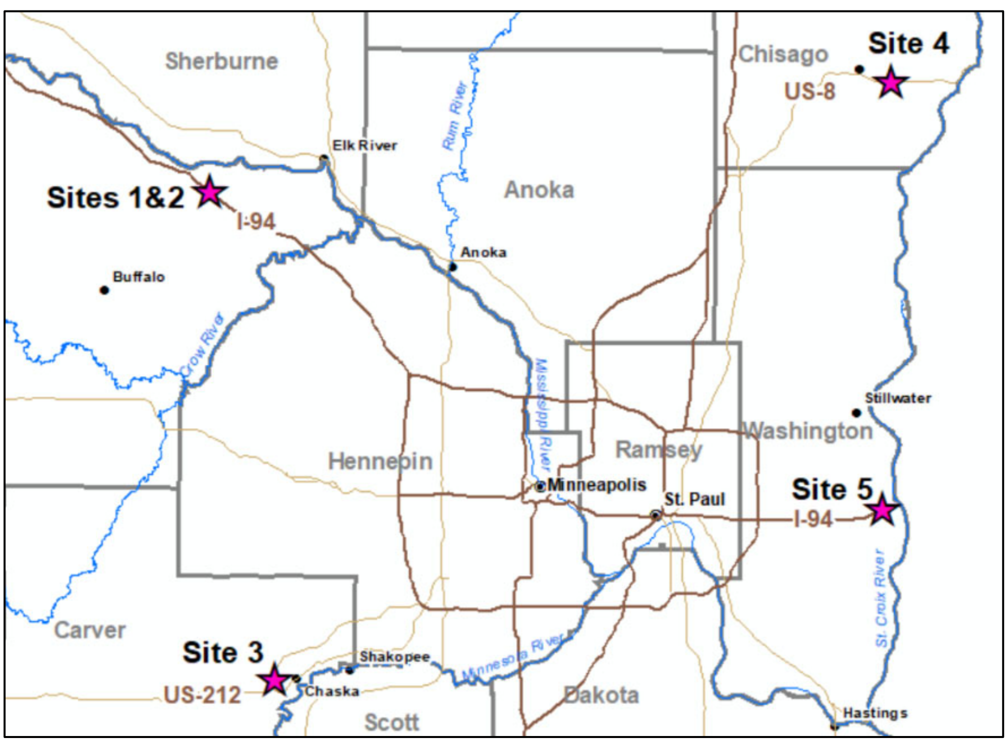


Figure 2: Five study sites were selected for this swale study, all on the periphery of the Twin Cites metro area.

The study swales do not include special treatment features such as check dams, engineered media, or special vegetation. The selected swales are likely 30-50 years old and installed prior to the CSW Permit original issuance, and as such, the swales would not have been explicitly designed to be infiltration areas.

The contributing watershed area of each swale along with the immediate watershed area of the study swale are shown in Table 1. The watershed area for each study swale was determined through review of topographic imagery, visual observation in the field, and field surveys. Swale dimensions and slopes were obtained through field surveys. The immediate study swale watershed boundary is defined as the total watershed area (i.e. area of surface flow contribution) of the downstream weir less the watershed area of the upstream weir.

Table 1: The immediate study swale watershed is the contributing watershed between the swales, which does not include the area upstream of the upstream weir. As such, the size of the immediate watershed of the study swale is the downstream weir's contributing watershed area less the upstream weir's contributing watershed area.

	Weir Watersheds		Immediate Study Swale Watershed		
	Upstream Weir Watershed	Downstream Weir Watershed	Watershed Area	Pervious Portion	Pervious Area
Site	(total acres)		(net acres)	(%)	(acres)
1	174.03	174.79	0.76	80%	0.61
2	0.00	0.64	0.64	60%	0.38
3	7.88	8.97	1.09	80%	0.87
4	3.26	4.40	1.14	73%	0.83
5	0.71	1.82	1.11	92%	1.02

The delineated watersheds for each site are shown in Figure 3 through Figure 7. The full watershed (including the upstream contributing area and the study swale) are illustrated with hashmarks and the weirs are shown as a red line.

Soils characterizations are discussed in detail within the *Design Criteria for Volume Reduction Practices* section later in this report.

Figure 3: Above: The delineated watershed upstream of the Site 1 upstream weir was estimated as 174.03 acres. This watershed is substantially larger than the other watersheds. Left: The Site 1 study swale watershed was 0.76 acres.

Figure 4: The Site 2 study swale watershed was estimated as 0.64 acres. Only one weir was necessary at Site 2 because the contributing area is relatively small.

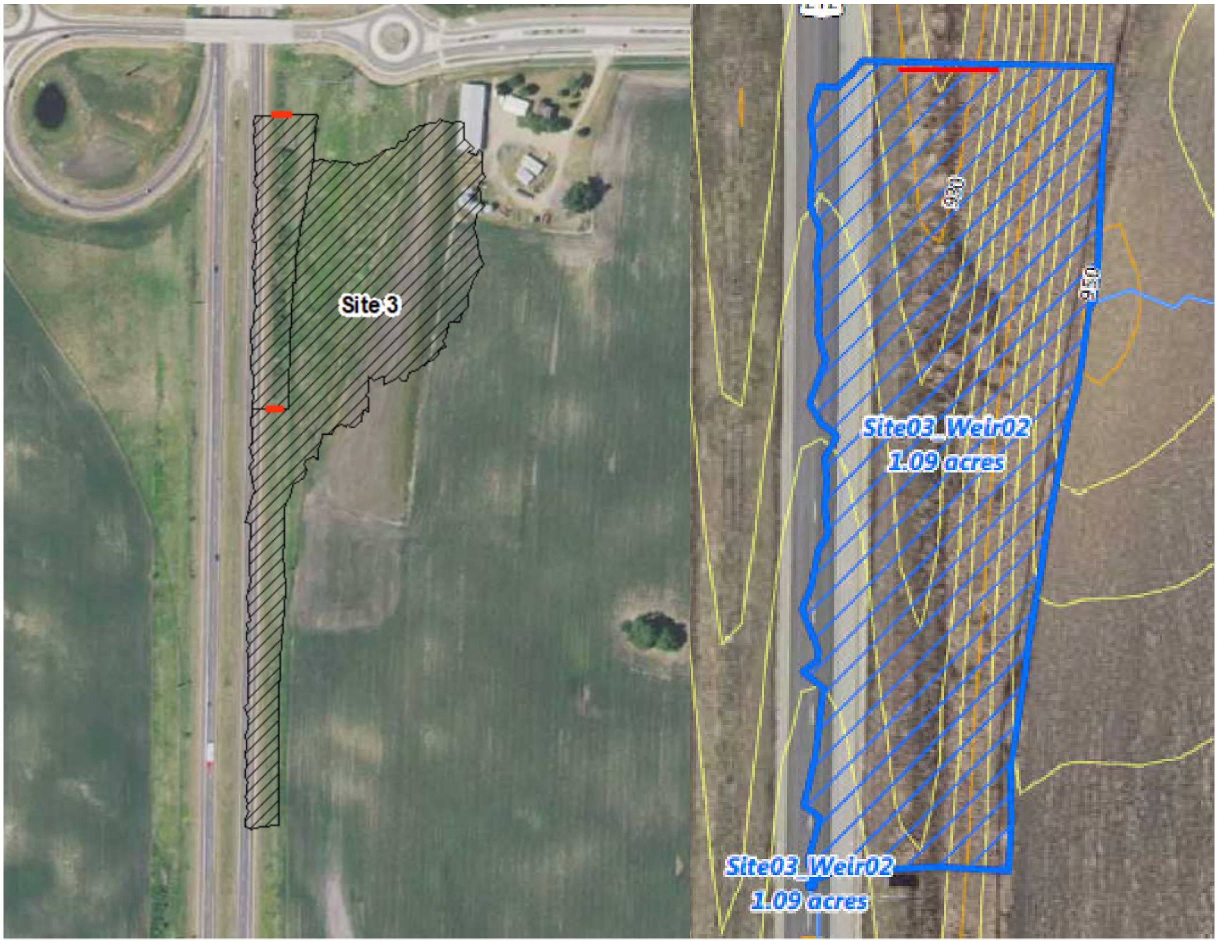


Figure 5: Left: The contributing area upstream of the Site 3 study swale was initially estimated as 7.9 acres, later revised to 3.44 acres. Right: The Site 3 study swale watershed was estimated as 1.09 acres

The land cover breakdown for Site 3 upstream of the study swale, the study swale, and the combined contributing area (to the downstream weir) are shown in Table 2.

Table 2: At Site 3, road surface comprised 20% of the immediate study swale watershed and 25% of the upstream watershed. The remaining portions include the swale and other grassed areas.

	Site 3					
	Immediate Study Swale Area		Upstream of Study Swale		Total Area to Study Swale	
Land cover	acres	%	acres	%	acres	%
Road	0.22	20%	0.66	28%	0.88	25%
Other Impervious	0.00	0%	0.00	0%	0.00	0%
Road-side swale/grass	0.37	34%	0.71	30%	1.09	32%
Grass-side swale/grass	0.51	46%	0.97	41%	1.48	43%
Total Impervious	0.22	20%	0.66	28%	0.88	25%
Total Pervious	0.88	80%	1.68	72%	2.56	75%
Total	1.09	100%	2.34	100%	3.44	100%

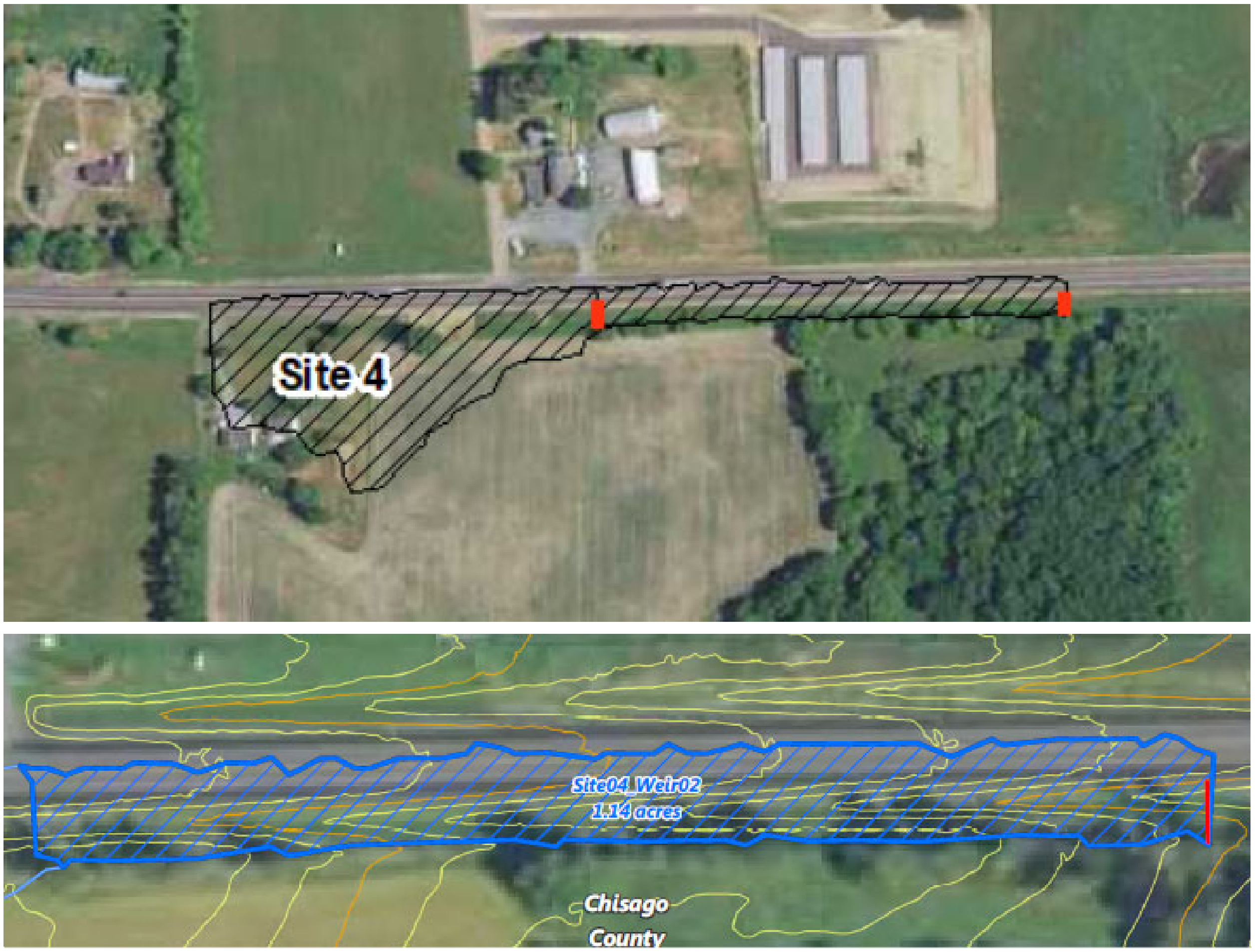


Figure 6: Top: The contributing area upstream of the Site 4 study swale was estimated as 3.3 acres. Bottom: The Site 4 study swale watershed was estimated as 1.14 acres.

The land cover breakdown for Site 4 upstream of the study swale, the study swale, and the combined contributing area (to the downstream weir) are shown in Table 3.

Table 3: At Site 4, road surface comprised 27% of the immediate study swale watershed and 10% of the upstream watershed. The remaining portions include the swale and other grassed areas.

	Site 4					
	Immediate Study Swale Area		Upstream of Study Swale		Total Area to Study Swale	
Land cover	acres	%	acres	%	acres	%
Road	0.31	27%	0.20	6%	0.50	12%
Other Impervious	0.00	0%	0.12	4%	0.12	3%
Road-side swale/grass	0.52	46%	1.84	57%	2.36	54%
Grass-side swale/grass	0.30	27%	1.07	33%	1.37	31%
Total Impervious	0.31	27%	0.32	10%	0.63	14%
Total Pervious	0.83	73%	2.91	90%	3.73	86%
Total	1.13	100%	3.23	100%	4.36	100%

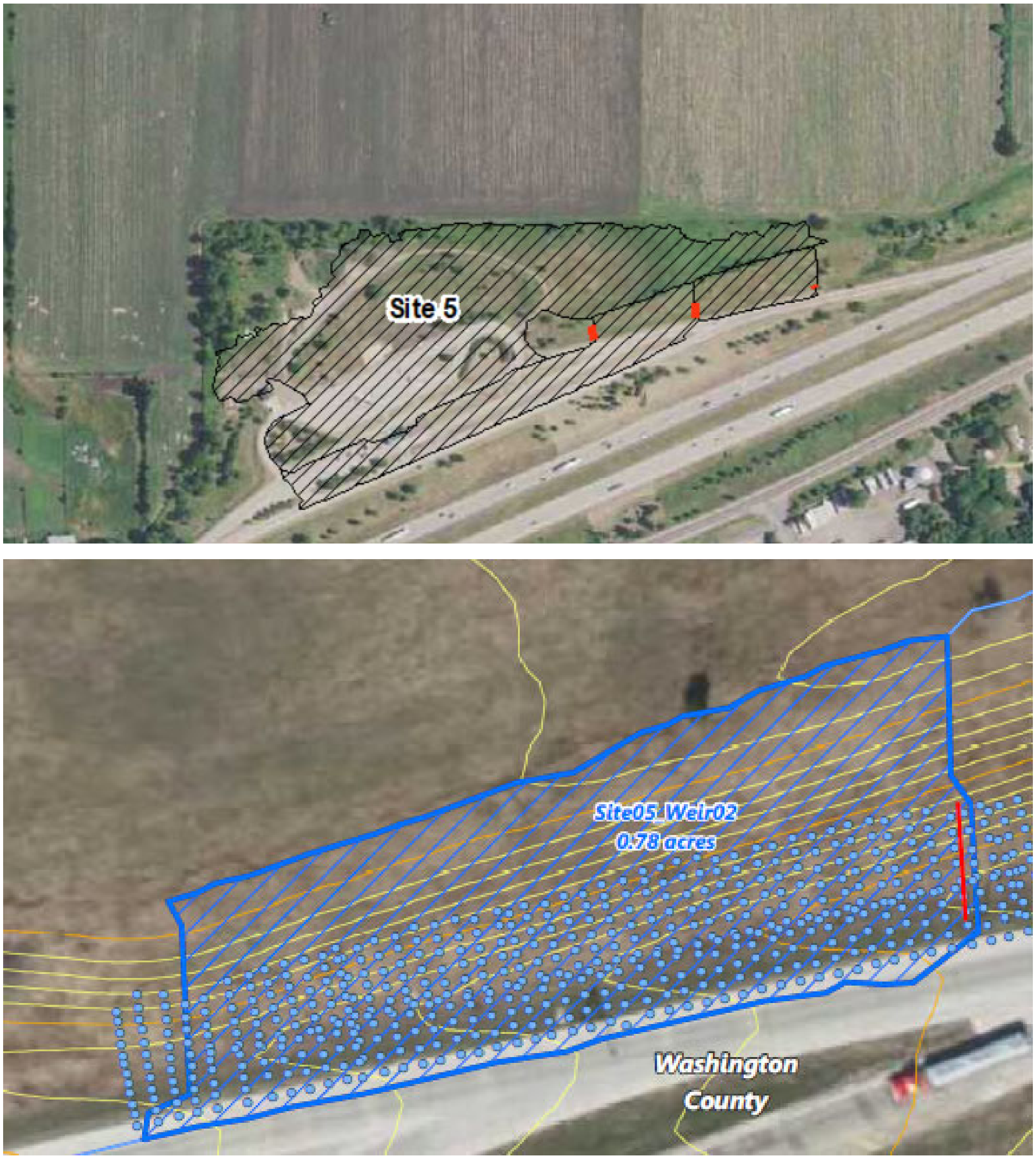


Figure 7: The Site 5 swale study watershed was 0.78 acres. The author was unable to differentiate the 5B and 5W watersheds or further contributing area details about this site.

In-field Water Budget Application

The first objective of this study was to quantify the volume removal occurring in road-side swales under field conditions, over varying time scales, using the water budget. This section details the water budget application methods, results by site and year, and a summary and discussion.

Water Budget Application Methods

The water budget is the mass balance accounting for the water inputs and outputs across a specified boundary; the sum of the inputs equals the sum of the outputs plus any change within that area. Figure 8 and Equation 1 illustrate the the water budget applied to a roadside swale.

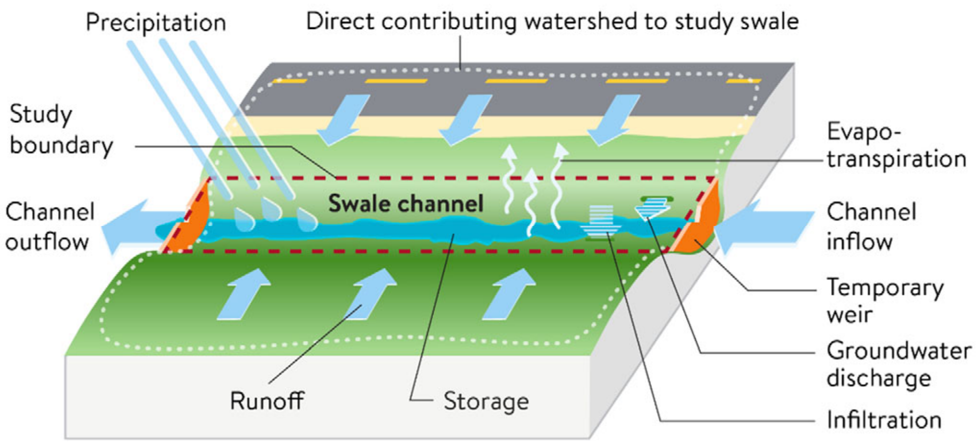


Figure 8: A water budget mass balance application uses a delineated boundary to track the inputs and outputs into the system. The boundary (red dotted line) is set at the top of the swale side slopes and at an arbitrary upstream and downstream location within the swale, where a weir was placed. A vertical boundary (not depicted) is between the top of the vegetation and the soil surface. Using this 3-dimensional boundary, all the inputs and outputs into the study swale are identified. The inputs include runoff, precipitation, groundwater discharge, and channel inflow. The outputs include evapotranspiration, channel outflow, and infiltration. The change in storage includes any precipitation stored in surface depressions or on the vegetation.

Some components of the water budget are difficult or impossible to measure. Therefore, considerations and assumptions can be applied to simplify the water budget application, as listed below. This simplified water budget application as shown in Figure 9 and Equation 2 is the basis for this study. Equation 2 is rearranged for the abstraction component, the value of interest for this study. Simplifications include:

1) If the study area boundary is moved outward from the swale boundary to the immediate study swale watershed boundary, the runoff component can be eliminated from the equation because the watershed boundary, by definition, is the runoff boundary.
2) Site selection can identify areas with soils and groundwater which are unlikely to lead to groundwater discharge, so groundwater discharge can be assumed negligible.
3) Infiltration, evapotranspiration, and local storage can be lumped together and referred to as abstraction. Abstraction refers to the portion of precipitation that does not result as runoff and is also equivalent to the “runoff volume reduction”. This term should not be confused with “initial abstraction” frequently used in hydrologic and hydraulic modeling, which describes the depth of precipitation that is abstracted prior to the initiation of runoff for any specific precipitation event.

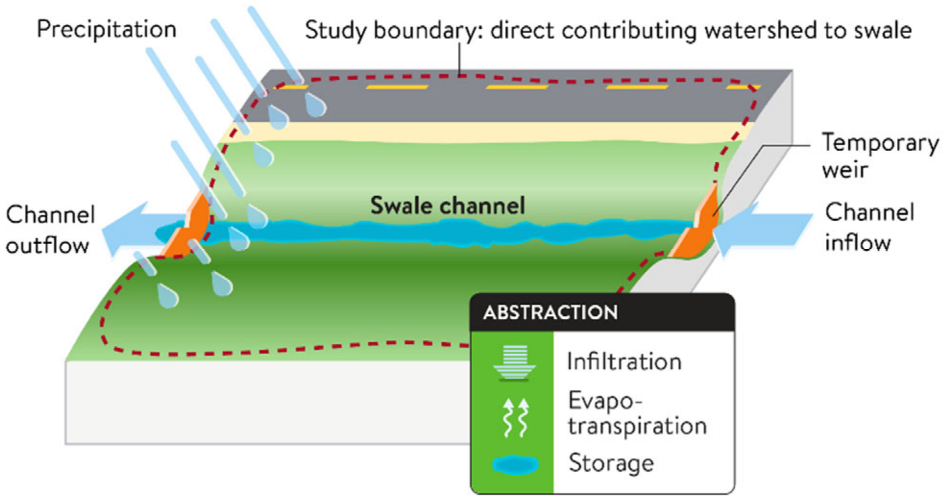


Figure 9: The simplified swale water budget uses the immediate watershed of the study swale as the study boundary and assumes groundwater discharge is negligible. Evapotranspiration, infiltration, and storage are lumped into the abstraction component. Therefore, the inputs are simplified to precipitation and channel inflow, and the outputs are simplified to channel outflow and abstraction.

$$V_{in,t} + P_t + RO_t + GW_{in,t} = V_{out,t} + I_t + ET_t + S_t \qquad \text{Equation 1}$$

Applying the above three simplifications, and rearranging results in the simplified water budget:

$$A_t = P_t + V_{in,t} - V_{out,t} \qquad \text{Equation 2}$$

Where:

t	=	Time period

Inputs

$V_{In,t}$	=	Swale channel inflow volume at the upstream study area boundary over time period t
P_t	=	Direct precipitation volume into the study area over time period t
RO_t	=	Direct runoff volume into the study area over time period t
GW_{In}	=	Groundwater discharge volume into the study area over time period t

Outputs

$V_{Out,t}$	=	Swale channel outflow volume at the downstream end of the study area over time period t
I_t	=	Infiltration within the study area boundary over time period t
ET_t	=	Evapotranspiration from within the study area over time period t
S_t	=	Stored water (interception, depressional storage, and detention) within the boundary over t
A_t	=	Abstraction over time period t. $A_t = S_t + ET_t + I_t$ = runoff volume reduction

The runoff ratio is the portion of precipitation that results as runoff or discharge from a watershed. Equation 3 shows the runoff ratio for the simplified water budget application. Runoff ratios were used as a high-level validation of the collected data. If the assumptions built in to the simplified water budget are accurate, runoff ratios can be expected to range from 0% and 100% (i.e. all of the precipitation is abstracted to none of the precipitation is abstracted and all runs off). Due to this application including an upstream watershed contribution, a negative runoff ratio could occur if the study swale infiltrates all of the precipitation from the immediate watershed and water from the upstream watershed. However, this case would only be expected in highly pervious soils in the study watershed coupled with less pervious soils in the upstream watershed, which was not the characterization results of these sites. Therefore, if the data and analysis are accurate and the assumptions in the simplified water budget are acceptable, a runoff ratio between 0 and 100% is expected and considered the “feasible range”. Runoff ratios outside of the feasible range would be due to flaws in the data or assumptions used for this analysis.

Using data and reference values in established literature, a narrower “reference range” for the runoff ratio was defined. The MPCA Watershed Pollutant Load Monitoring Network (WPLMN) measures and calculates runoff ratios at the major (HUC-8) watershed scale over a multi-year period. The WPLMN runoff ratios in Minneapolis-St. Paul metro area over roughly the same time range of the study were about 25-40%. However, runoff ratios are dependent on site-specific conditions and may be substantially higher or lower than the watershed-scale runoff ratio. The MN Stormwater Manual summarizes runoff coefficients for different soil groups and slopes (McCuen, 2017), showing that runoff coefficients (aka ratios) can vary substantially depending on the land use and hydrologic soil group. Combining these sources, the selected runoff ratio reference range for this project (for comparative purposes only) is 20-80% for precipitation events above some minimal precipitation depth. Runoff ratios outside of the reference range are suspicious but feasible.

Converse to the runoff ratio, the abstraction ratio (Equation 4) is the portion of precipitation that is abstracted (infiltrated, evaportranspirated, or stored) in that watershed. For the simplified water budget application, the abstraction ratio and runoff ratio sum to one or 100% because all other outputs from the system are assumed negligible in the simplified water budget.

$$\boldsymbol{Runoff\ Ratio_t = \frac{V_{out,t} - V_{in,t}}{P_t}}$$ Equation 3

$$\boldsymbol{Abstraction\ Ratio_t = \frac{A_t}{P_t}}$$ Equation 4

Where:

A_t	=	Abstraction volume within the study area over time period t
$V_{In,t}$	=	Swale channel inflow volume at the swale upstream boundary over time period t
$V_{Out,t}$	=	Swale channel outflow volume at the swale downstream boundary over time period t
P_t	=	Direct precipitation volume into the study area over time period t
t	=	Time period

The five swales were equipped with an upstream and a downstream 90-degree contracted V-notch weir (Figure 10), a pressure transducer to measure the water level upstream of each weir, and a rain gauge to measure precipitation depth. Refer to the Appendix A for a detailed description of the swale set-ups. Site 2 required only one weir because the watershed was small, and two weirs were not necessary to isolate the study area.

Figure 10: The study swales were equipped with V-notch weirs that were installed and maintained through the project. This photo shows the Site 3 downstream weir. The same weir, during the growing season, is featured on the report cover.

The data were stored in an on-site logger and downloaded at roughly bi-weekly site visits, at which time the equipment was inspected and drifts or other issues addressed. Data were imported, corrected, and analyzed in Excel by the original project team.

Corrected stage data were converted to flowrates using the Cone equation at each time step (Equation 5, USBR).

$$Q = 2.49 * h^{2.48}$$ **Equation 5**

Where:

Q = Flowrate (ft^3/sec)

h = Stage above the weir (ft)

Swale channel inflow ($V_{In,t}$) and swale channel outflow ($V_{Out,t}$) volumes were calculated by multiplying the calculated flowrate by the time step length and then summing over the full time period as shown in Equation 6.

$$V_T = \sum_{i=1}^{n} Q_i * t_i$$ **Equation 6**

Where:

V_T = Flow volume over time period T

n = Number of time steps in time period T

Q_i = Flowrate in the i^{th} time step

T_i = Length of time of the i^{th} time step

Precipitation volumes were calculated using the precipitation depth multiplied by the watershed area as shown in Equation 7. Off-site precipitation data were used to estimate precipitation when equipment failures occurred.

$$P_T = \sum_{i=1}^{n} p_i * t_i * a \qquad \text{Equation 7}$$

Where:

P_T	=	Precipitation volume over time period T
n	=	Number of time steps in time period T
p_i	=	Precipitation depth at the i^{th} time step
t_i	=	Length of time of the i^{th} time step
a	=	Watershed area

Flow and precipitation data were analyzed at seasonal and event scales, which define the time period T for each application. Seasons were generally defined as May 1 through November 30 to avoid snow and freezing conditions. Individual rainfall-runoff events were defined by the original project team based on observation of precipitation and flow data. The event start was defined as the start of precipitation during no/low flow conditions and the end was defined as the return of flow to the no/low flow conditions. Multiple storms could be combined into a single event if the flow did not drop to the no/low flow condition condition between rainfalls.

Event-based rainfall versus runoff volume data per site and season were plotted in excel and a linear trendline and cooresponding R^2 value were added to the data points to characterize the consistency of the data. Along with the collected data, the 0% and 100% runoff ratio (feasible range) lines were plotted for context.

An abstraction rate (in inches per hour) was calculated at a seasonal and rainfall-runoff event scale per site by dividing the event abstraction volume (Equation 8) by the product of the event duration and impervious area within the study swale watershed area. Since this study used the immediate watershed of the swale and could not isolate just the swale, the rate applies to the entire impervious area within the immediate swale watershed. This analysis assumes that no water is abstracted by the impervious areas in the swale watershed.

$$Abstraction\ Rate_t = \frac{A_t}{t \times a_{imp}} \qquad \text{Equation 8}$$

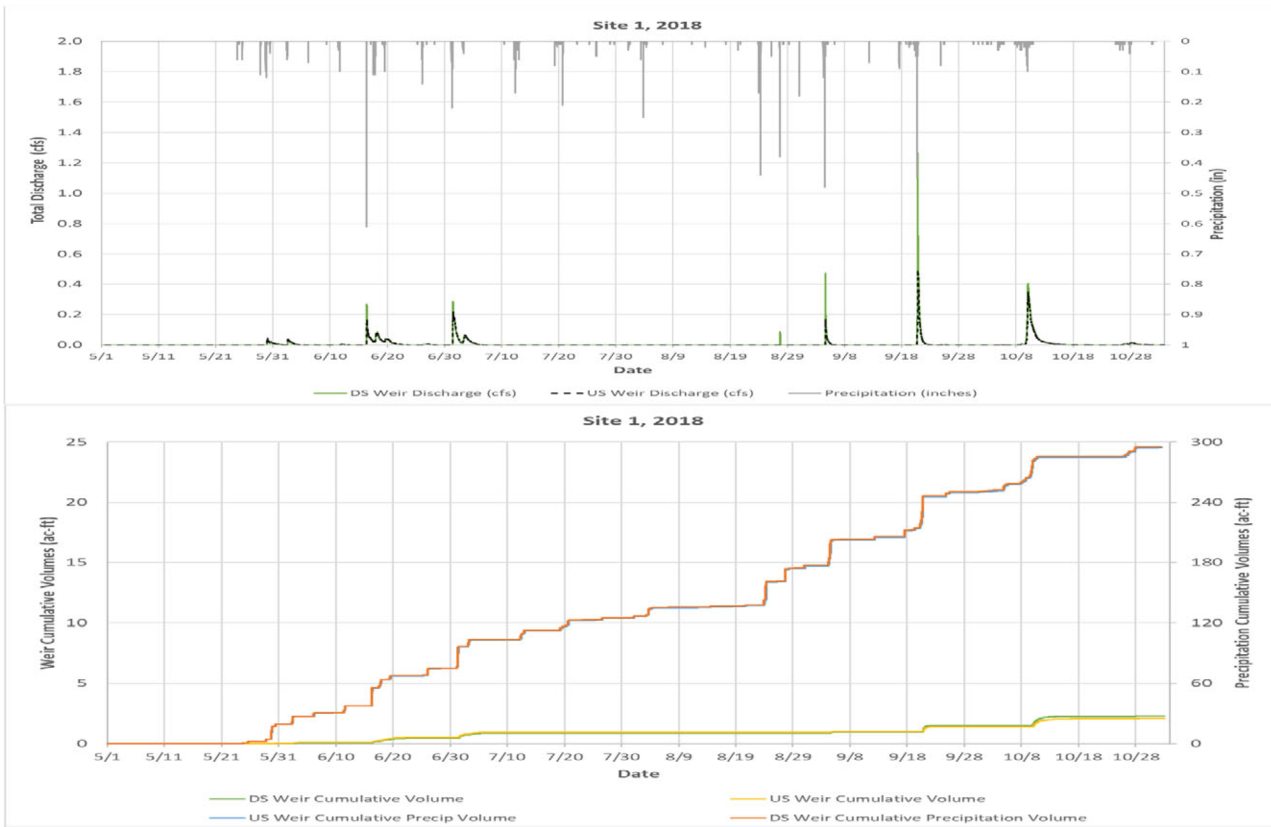
Where:

A_t	=	Abstraction volume within the study swale watershed area during duration t (acre-in)
t	=	Duration of rainfall-runoff event (hours)
a_{imp}	=	Impervious area of immediate swale watershed (acres)

Water Budget Application Results

Site 1, 2018

A hydrograph and precipitation plot, a cumulative flow and precipitation volume plot, and tabulated seasonal flow, precipitation, and runoff and abstraction ratios for Site 1 in 2018 are shown in Figure 11.



				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed				
Site, Year	Start Date	End Date	Precip (inches)	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	**Abstraction Ratio**
1, 2018	5/20	11/1	20.1	176.06	2.12	294.31	**0.7%**	176.82	2.32	295.58	**0.8%**	0.76	0.19	1.27	**15%**	**85%**

Figure 11: Site 1, 2018 precipitation and hydrograph (top) result in the cumulative precipitation and flow plots (middle) and the seasonal runoff and infiltration tabulated data (bottom).

In 2018, the Site 1 study swale showed a seasonal runoff ratio of 15% with a corresponding abstraction ratio of 85%. The runoff ratios at the upstream and downstream weirs (considering the whole upstream watershed) were 0.7% and 0.8%, which is excessively low compared to reference range. The author suspects that the upstream watershed was overestimated, hence the very low runoff ratios derived from the entire upstream watershed area.

The event-based rainfall-runoff analysis (Table 4) provides additional insight into the runoff ratios. Of the seven identified precipitation-runoff events, precipitation was similar for five events (events 1, 3, 5-7), ranging from 1.78-2.43 inches. Because of the similar precipitation volumes, the resultant flow volume should be somewhat similar (but vary based on the intensity of the storm, vegetation size, soil moisture, groundwater level, and other environmental parameters). For instance, as commonly observed in rainfall-runoff data, the runoff ratio may be expected to generally show a decreasing trend through the season as vegetation grows larger and is able to intercept and transpire more water (assuming other important parameters remain somewhat constant). However, the runoff ratio for these

similar precipitation events increased from -38% to 95% through the season, with only one event falling within the reference range.

Table 4: Seven rainfall-runoff events were identified at Site 1 in 2018 ranging from three to 10 days in duration. The event-based runoff ratios for Site 1 study swale in 2018 varied from -38% to 95%.

				Upstream Weir		Downstream Weir		Study Swale Immediate Watershed					
Event	Start	Duration (days)	Precip (inches	Precip Volume (ac-ft)	Flow Volume (ac-ft)	Precip Volume (ac-ft)	Flow Volume (ac-ft)	Precip Volume (ac-ft)	Flow Volume (ac-ft)	Abstraction Volume (ac-ft)	Abstraction Rate (in/hr)	**Runoff Ratio**	**Abstraction Ratio**
1	5/28/18	10.2	1.91	28.02	0.12	28.14	0.08	0.12	-0.05	0.17	0.01	**-38%**	**138%**
2	6/11/18	3.0	0.46	6.75	0.01	6.78	0.00	0.03	-0.01	0.03	0.01	**-18%**	**118%**
3	6/16/18	8.0	2.05	30.08	0.40	30.21	0.37	0.13	-0.03	0.16	0.02	**-22%**	**122%**
4	6/26/18	3.0	0.47	6.90	0.02	6.93	0.01	0.03	-0.01	0.04	0.01	**-26%**	**126%**
5	7/1/18	6.0	1.91	28.02	0.41	28.14	0.41	0.12	0.00	0.12	0.02	**1%**	**99%**
6	9/4/18	3.0	1.78	26.12	0.08	26.23	0.13	0.11	0.05	0.06	0.02	**46%**	**54%**
7	9/20/18	6.7	2.43	35.65	0.37	35.81	0.52	0.15	0.15	0.01	0.00	**95%**	**5%**

A plot of the event-based rainfall-runoff events (Figure 12) illustrates the variability of the runoff ratios, which indicates a weak trend and low R^2 value. A potential cause for the increase in the event-based runoff ratio through the season is that water was circumventing the downstream weir or monitoring equipment earlier in the season and was filled as the season progressed, either by vegetative growth, settling, or human manipulation. An alternate cause could be that the seasonally-high groundwater table increased through the season, hence decreasing the ability of the soil to accept precipitation. However, the variability of the runoff ratio seems not fully explained by raising groundwater. Other potential issues with this site's data could include equipment or analysis errors. Due to these issues, the Site 1 2018 data for the study swale is considered to be of low confidence in data validity.

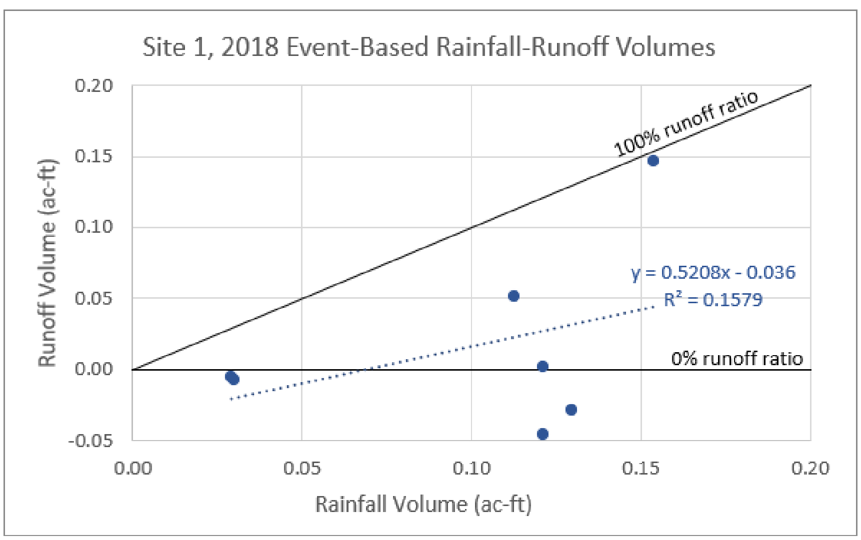
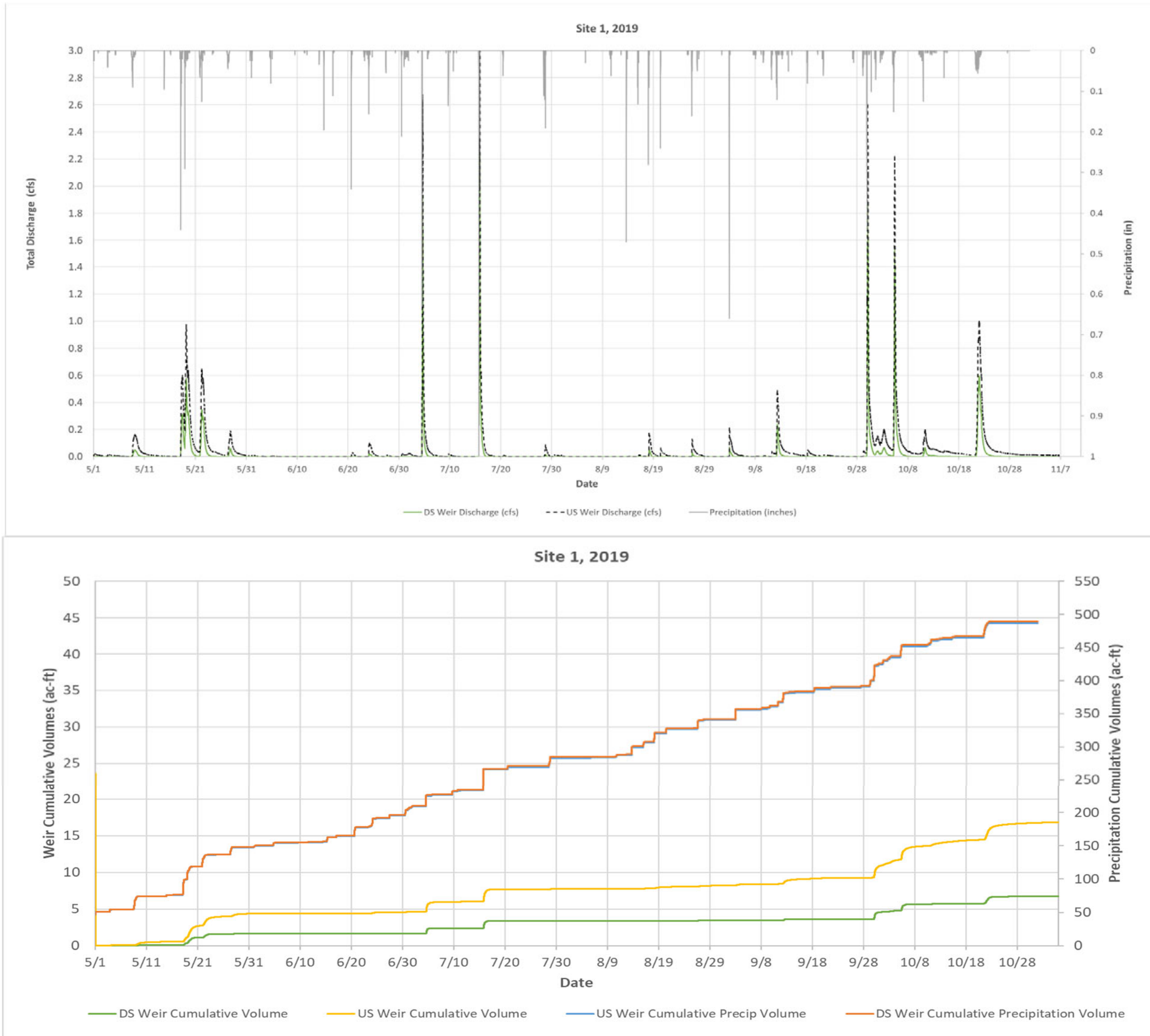


Figure 12: The event-based rainfall runoff volumes spanned a wide range, and the trendline for the events shows a weak relationship with an R^2 of 0.16.

Site 1, 2019

A hydrograph and precipitation plot, a cumulative flow and precipitation volume plot, and tabulated seasonal flow, precipitation, and runoff and abstraction ratios for Site 1 in 2019 are shown in Figure 13.



				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed				
Site, Year	Start Date	End Date	Precip (inches)	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	**Abstraction Ratio**
1, 2019	5/1	10/30	30.0	176.06	16.71	440.30	**3.8%**	176.82	6.70	442.20	**1.5%**	0.76	-10.01	1.90	**-527%**	**627%**

Figure 13: Site 1, 2019 precipitation and hydrograph (top) result in the cumulative precipitation and flow plots (middle) and the seasonal runoff and infiltration tabulated data (bottom).

In 2019, The Site 1 study swale showed a seasonal runoff ratio of -527% with a corresponding abstraction ratio of 627%. This huge abstraction ratio indicates error with the data, possibly due to most water circumventing the downstream weir or equipment or monitoring equipment errors. These values are also inconsistent with this site's 2018 results, and flow by-passing the downstream weir or monitoring equipment was also suspected at this site early in 2018. The runoff ratios associated with the full upstream watershed were also suspiciously low (3.8% and 1.5%), as they were at this site in the previous year. However, this year's values are substantially larger than the previous year's values of

0.7% and 0.8%, providing further evidence that the weirs may have been circumvented at this site in 2018. Event based rainfall-runoff data (Figure 14) did not appear to have a seasonally based trend as was seen at the site in 2018 (which offers evidence that the circumventing flow at the downstream weir was slowly directed to the weir through the season). However, increasing precipitation consistently resulted in less runoff as calculated for the study swale and hence, a lower runoff ratio. In fact, this site and year showed one of the strongest relationships between rainfall and runoff with a R^2 value of 0.89 (Figure 14). However, no positive runoff ratios were observed.

These factors point to flow circumventing the downstream weir or monitoring equipment error. Due to these issues, data relevant to the study swale is not valid. Flow data at the upstream weir could be valid, however, the likely case that the upstream watershed is substantially overestimated means that deducing the water budget parameters from this case would not be valid.

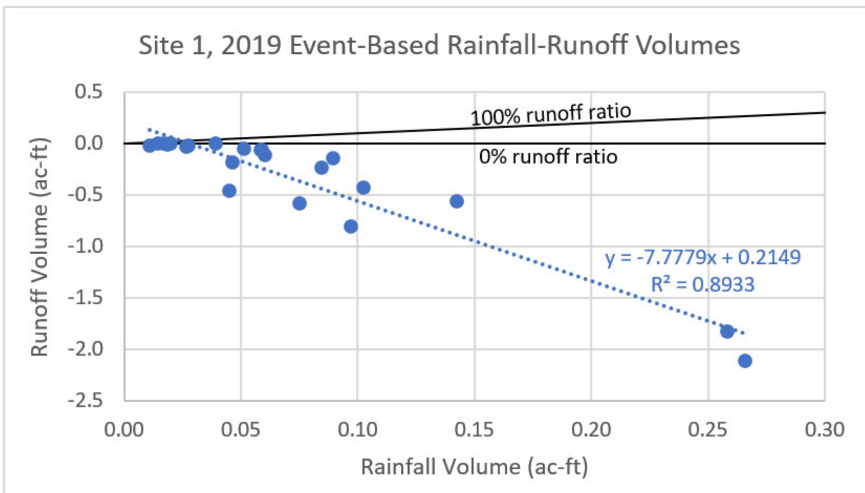
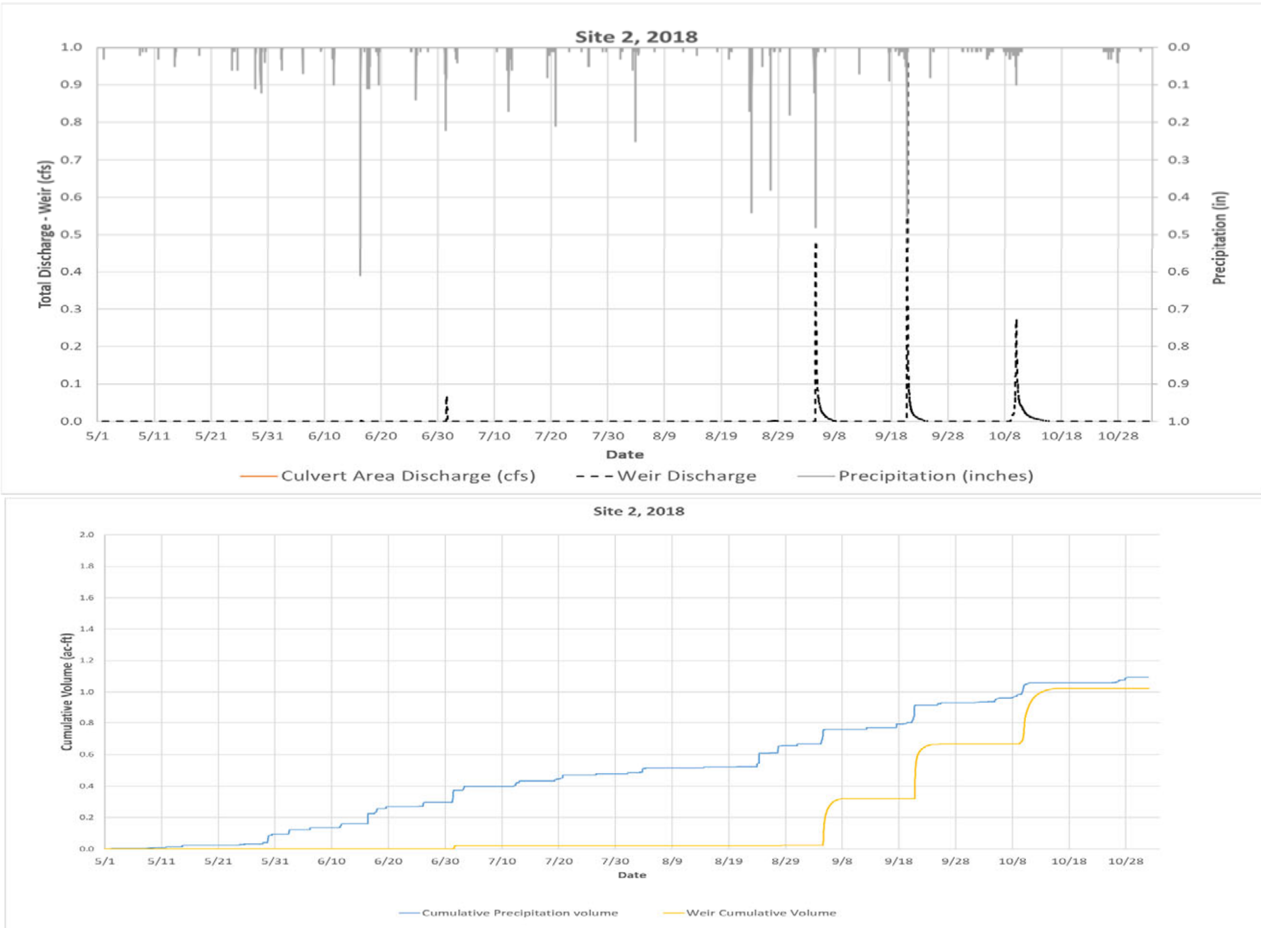


Figure 14: The event-based rainfall-runoff relationship for the Site 1 study watershed in 2019 showed an unlikely-to-be accurate but strong trend (R^2 of 0.89). Flow circumventing the downstream weir or equipment is the suspected cause.

Site 2, 2018

A hydrograph and precipitation plot, a cumulative flow and precipitation volume plot, and tabulated seasonal flow, precipitation, and runoff and abstraction ratios for Site 2 in 2018 are shown in Figure 15.



				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed				
Site, Year	Start Date	End Date	Precip (inches)	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	**Abstraction Ratio**
2, 2018	9/1	11/1	8.1	N/A				represented in info at right				0.64	1.00	0.43	**233%**	**-133%**

Figure 15: Site 2, 2018 precipitation and hydrograph (top) result in the cumulative precipitation and flow plots (middle) and the seasonal runoff and infiltration tabulated data (bottom).

At a seasonal scale, 2018 Site 2 data indicated a runoff ratio of 233% and a corresponding abstraction ratio of -133%. This value indicates serious issues with the data, as a runoff ratio over 100% is not possible if all project assumptions and application are valid. Furthermore, upon inspection of the cumulative precipitation and flow plot, nearly all flow was measured during only three events, where each event resulted in a similar flow volume despite being substantially different precipitation volumes. Seasonal precipitation was also very low, indicating potential errors in measurement. The event-based analyses (Table 5 and Figure 16) further illustrate the issues with these data. The reason for these issues is unclear, but equipment malfunction or vastly different site hydrology than assumed could be responsible. These data are considered invalid.

Table 5: Three rainfall-runoff events were identified at Site 2 in 2018. The event-based runoff ratios for the Site 2 study swale in 2018 varied from 193% to 290%.

			Study Swale Immediate Watershed					
Event	Start	Duration (days)	Precip Volume (ac-ft)	Flow Volume (ac-ft)	Abstraction Volume (ac-ft)	Abstraction Rate (in/hr)	**Runoff Ratio**	**Abstraction Ratio**
1	9/3/2018	2	0.09	0.26	-0.17	-0.11	289%	-189%
2	9/17/2018	4	0.15	0.29	-0.14	-0.05	193%	-93%
3	10/7/2018	4	0.1	0.29	-0.19	-0.06	290%	-190%

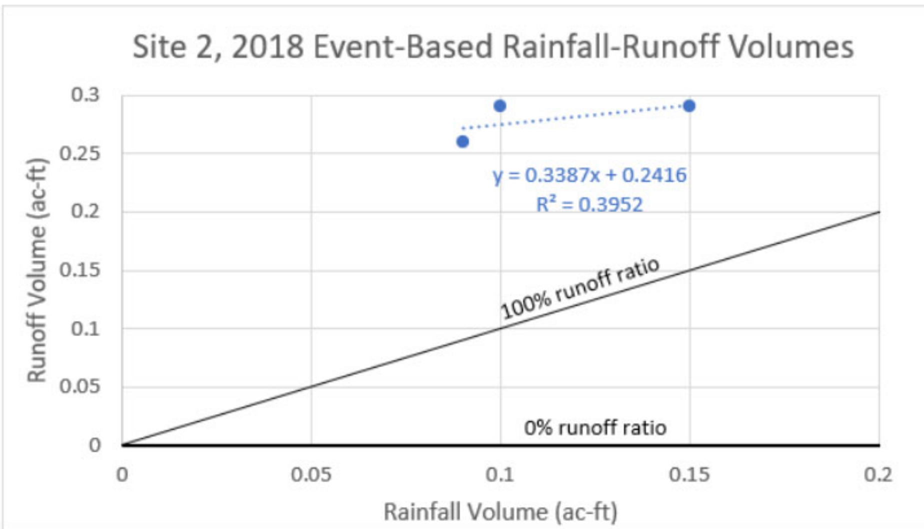
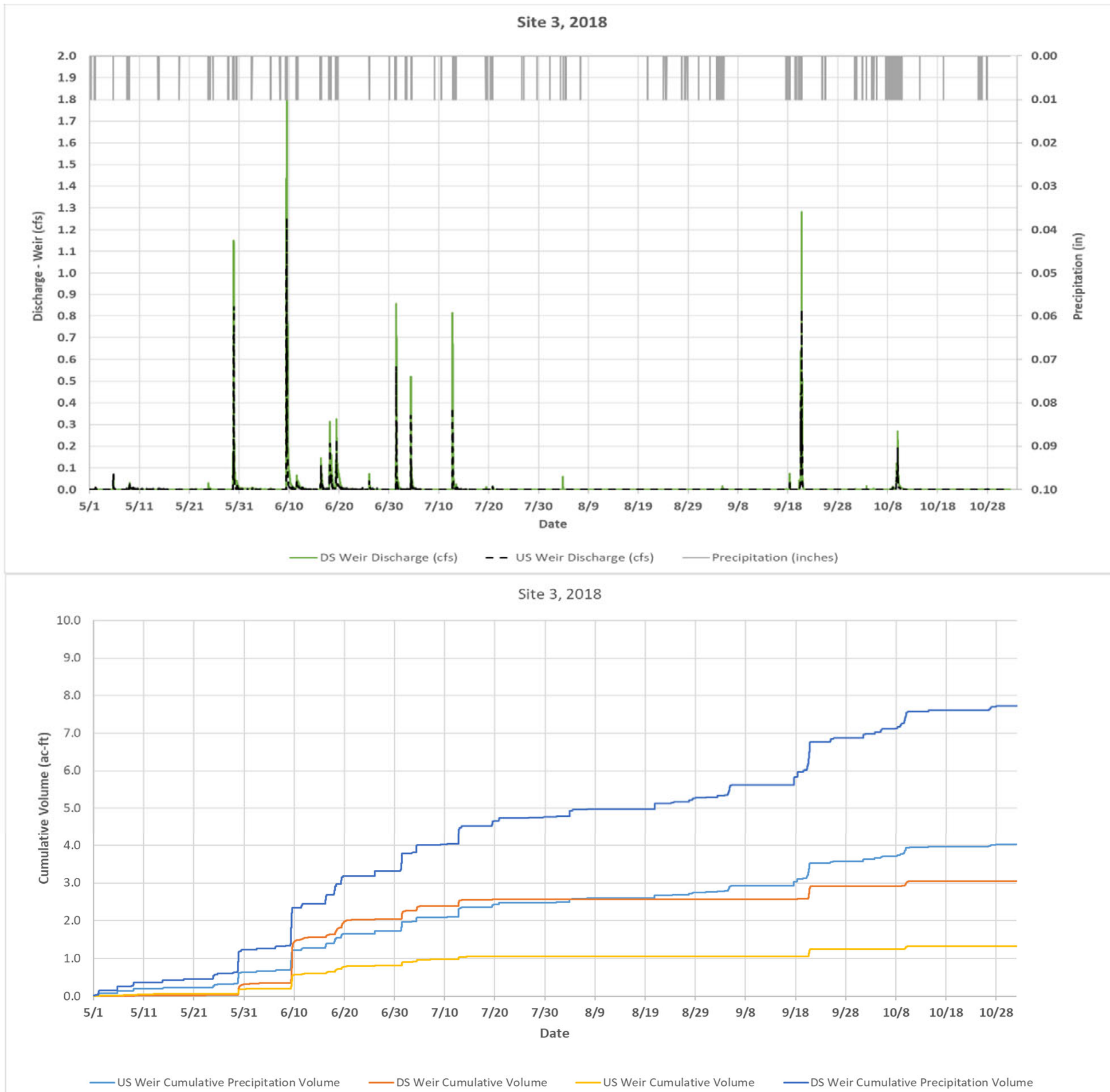


Figure 16: The three recorded rainfall-runoff events each had much more than 100% runoff ratio. The data at this site are considered invalid.

Site 3, 2018

A hydrograph and precipitation plot, a cumulative flow and precipitation volume plot, and tabulated seasonal flow, precipitation, and runoff and abstraction ratios for Site 1 in 2018 are shown in Figure 17.



				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed				
Site, Year	Start Date	End Date	Precip (inches)	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	**Abstraction Ratio**
3, 2018	4/28	11/1	26.9	1.79	1.33	4.02	**33%**	3.44	3.06	7.73	**40%**	1.65	1.73	3.71	**47%**	**53%**

Figure 17: Site 3, 2018 precipitation and hydrograph (top) result in the cumulative precipitation and flow plots (middle) and the seasonal runoff and infiltration tabulated data (bottom).

In 2018, the Site 3 study swale showed a seasonal runoff ratio of 47% with a corresponding abstraction ratio of 53%. This is one of few sites and years in this study where the runoff ratio is within the reference range. The upstream weir showed a seasonal runoff ratio of 33%, which may indicate that the upstream

watershed was overestimated or that abstraction was distinctly greater in the upstream area. The area associated with this watershed area was revised mid-project by the original project team, indicating some uncertainty in the contributing area.

The event-based rainfall-runoff data (Table 6) shows how the runoff ratio varied through the year. Between April and mid-May, runoff ratios were below zero, which could indicate that all precipitation was being infiltrated into the soil, or as was postulated for Site 1, that runoff was circumventing the downstream weir. Runoff ratios were largest between late May through Early July, including the 3.6" precipitation event starting on June 6 where the runoff ratio was calculated at 140%. This higher value could be associated with equipment error or groundwater discharge. On September 17, a 4-inch precipitation event resulted in just a 25% runoff ratio. Rain events under one inch of precipitation generally produced little to no runoff, particularly between mid-July and the beginning of September (gray rows of table). The lack of runoff during this time frame may be due to peak vegetative conditions and the ability of the vegetation to intercept and absorb precipitation in addition to the drier antecedent conditions due to larger gaps in precipitation events during this time.

Table 6: Thirty-one rainfall-runoff events were identified at Site 3 in 2018. The event-based runoff ratios varied from -16% to 140%.

				Upstream Weir		Downstream Weir		Study Swale Immediate Watershed					
Event	Start	Duration (days)	Event Precip (inches)	Precip Volume (ac-ft)	Runoff Volume (ac-ft)	Precip Volume (ac-ft)	Runoff Volume (ac-ft)	Precip Volume (ac-ft)	Runoff Volume (ac-ft)	Abstraction Volume (ac-ft)	Abstraction Rate (in/hr)	**Runoff Ratio**	**Abstraction Ratio**
1	4/29/18	4.0	0.56	0.084	0.013	0.161	0.001	0.077	-0.012	0.09	0.01	**-16%**	**116%**
2	5/5/18	1.0	0.36	0.054	0.008	0.103	0.004	0.050	-0.004	0.05	0.03	**-8%**	**108%**
3	5/8/18	2.0	0.37	0.055	0.016	0.106	0.013	0.051	-0.003	0.05	0.02	**-6%**	**106%**
4	5/14/18	1.5	0.20	0.030	0.004	0.057	0.002	0.028	-0.002	0.03	0.01	**-7%**	**107%**
5	5/18/18	1.0	0.63	0.094	0.000	0.181	0.001	0.087	0.001	0.09	0.05	**1%**	**99%**
6	5/28/18	3.0	2.16	0.322	0.127	0.619	0.281	0.297	0.153	0.14	0.03	**52%**	**48%**
7	6/2/18	1.0	0.15	0.022	0.001	0.043	0.009	0.021	0.008	0.01	0.01	**40%**	**60%**
8	6/6/18	4.0	3.72	0.555	0.372	1.066	1.090	0.512	0.718	-0.21	-0.03	**140%**	**-40%**
9	6/11/18	1.5	0.40	0.060	0.023	0.115	0.058	0.055	0.035	0.02	0.01	**64%**	**36%**
10	6/16/18	4.5	2.53	0.377	0.184	0.725	0.443	0.348	0.259	0.09	0.01	**74%**	**26%**
11	6/26/18	1.0	0.50	0.075	0.007	0.143	0.016	0.069	0.009	0.06	0.03	**14%**	**86%**
12	7/1/18	1.5	1.58	0.236	0.099	0.453	0.217	0.217	0.118	0.10	0.04	**54%**	**46%**
13	7/3/18	2.0	0.81	0.121	0.056	0.232	0.116	0.111	0.060	0.05	0.01	**54%**	**46%**
14	7/9/18	2.0	0.09	0.013	0.000	0.026	0.000	0.012	0.000	0.01	0.00	**0%**	**100%**
15	7/12/18	2.0	1.74	0.260	0.074	0.499	0.168	0.239	0.094	0.14	0.04	**39%**	**61%**
16	7/19/18	2.5	0.75	0.112	0.001	0.215	0.004	0.103	0.003	0.10	0.02	**3%**	**97%**
17	7/29/18	0.5	0.04	0.006	0.000	0.011	0.000	0.006	0.000	0.01	0.01	**0%**	**100%**
18	8/1/18	1.0	0.07	0.010	0.000	0.020	0.000	0.010	0.000	0.01	0.01	**0%**	**100%**
19	8/3/18	2.0	0.63	0.094	0.000	0.181	0.003	0.087	0.003	0.08	0.02	**4%**	**96%**
20	8/7/18	1.0	0.04	0.006	0.000	0.011	0.000	0.006	0.000	0.01	0.00	**0%**	**100%**
21	8/20/18	1.5	0.53	0.079	0.000	0.152	0.000	0.073	0.000	0.07	0.03	**0%**	**100%**
22	8/24/18	1.0	0.16	0.024	0.000	0.046	0.000	0.022	0.000	0.02	0.01	**0%**	**100%**
23	8/27/18	2.0	0.35	0.052	0.000	0.100	0.000	0.048	0.000	0.05	0.01	**0%**	**100%**
24	8/31/18	1.0	0.08	0.012	0.000	0.023	0.000	0.011	0.000	0.01	0.01	**0%**	**100%**
25	9/1/18	4.1	1.12	0.167	0.000	0.321	0.004	0.154	0.004	0.15	0.02	**2%**	**98%**
26	9/17/18	4.5	4.01	0.598	0.203	1.150	0.340	0.551	0.137	0.41	0.05	**25%**	**75%**
27	9/24/18	1.5	0.34	0.051	0.000	0.097	0.000	0.047	0.000	0.05	0.02	**0%**	**100%**
28	10/1/18	5.0	0.86	0.128	0.000	0.247	0.004	0.118	0.004	0.11	0.01	**3%**	**97%**
29	10/7/18	4.0	1.63	0.243	0.072	0.467	0.131	0.224	0.059	0.16	0.02	**26%**	**74%**
30	10/14/18	1.0	0.07	0.010	0.001	0.020	0.000	0.010	0.000	0.01	0.01	**-1%**	**101%**
31	10/26/18	2.5	0.43	0.064	0.000	0.123	0.002	0.059	0.001	0.06	0.01	**2%**	**98%**

This event-based rainfall-runoff analysis shows a moderate correlation when comparing events (Figure 18). The R^2 of 0.60 is within the moderate range of values in this study, and the seasonal runoff ratio seems to fall within the expected range compared to reference range. Overall, the confidence in the reliability of this data is moderate. However, because the data vary substantially from the same site just one year later, confidence in the validity of the data may be lower.

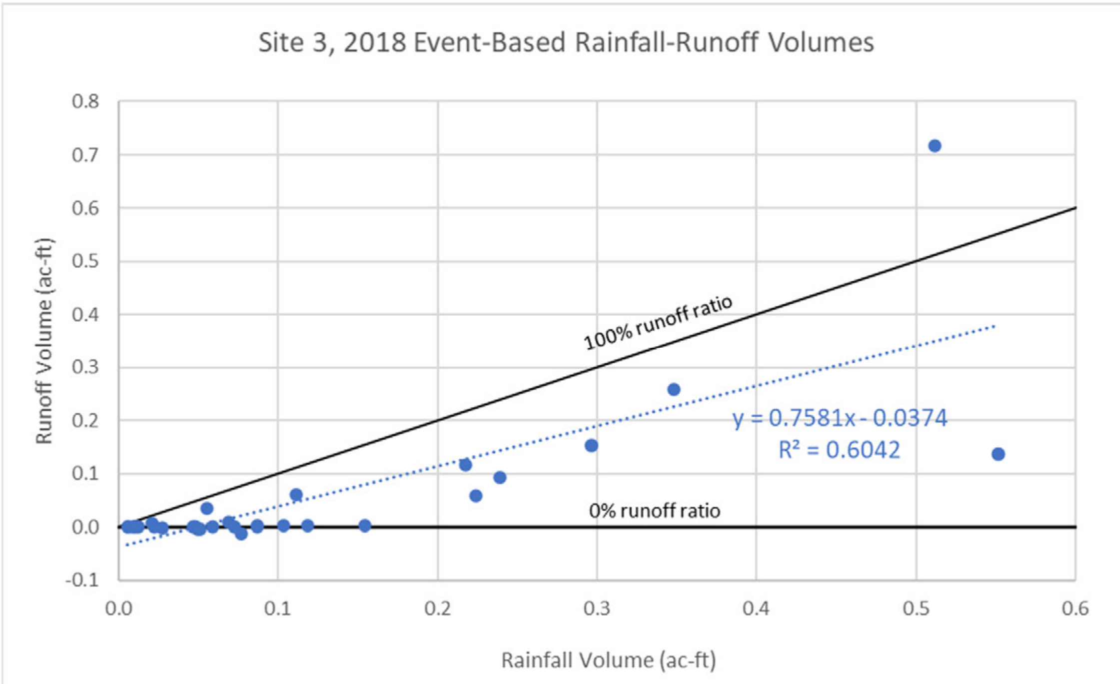
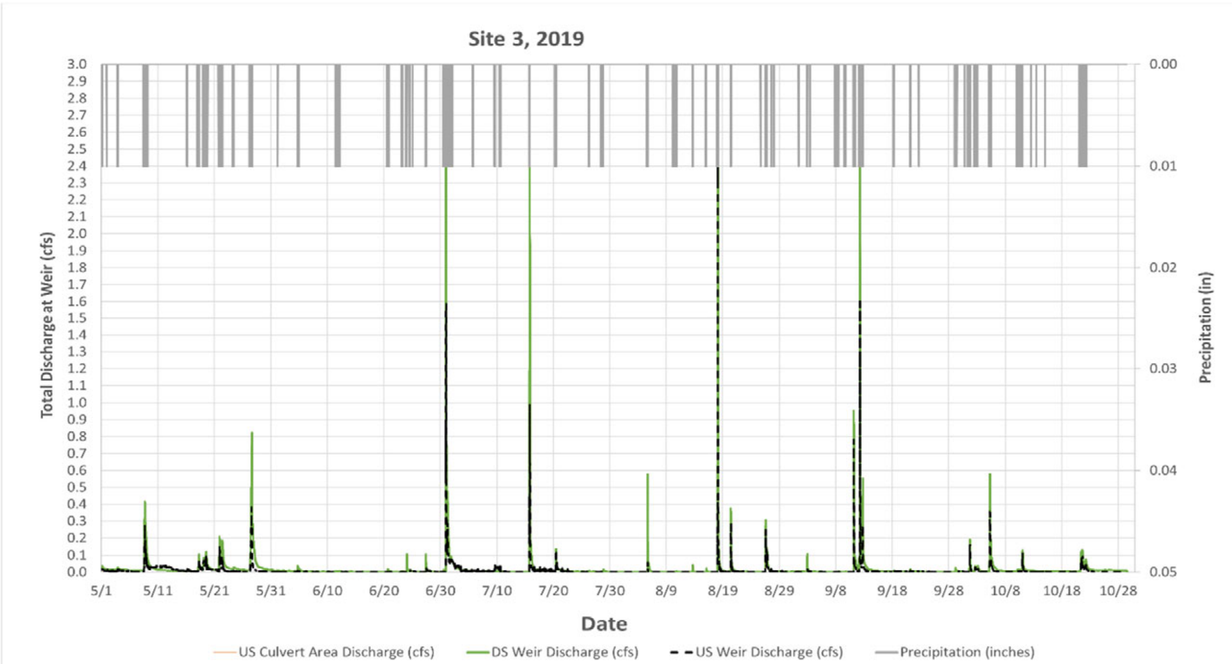
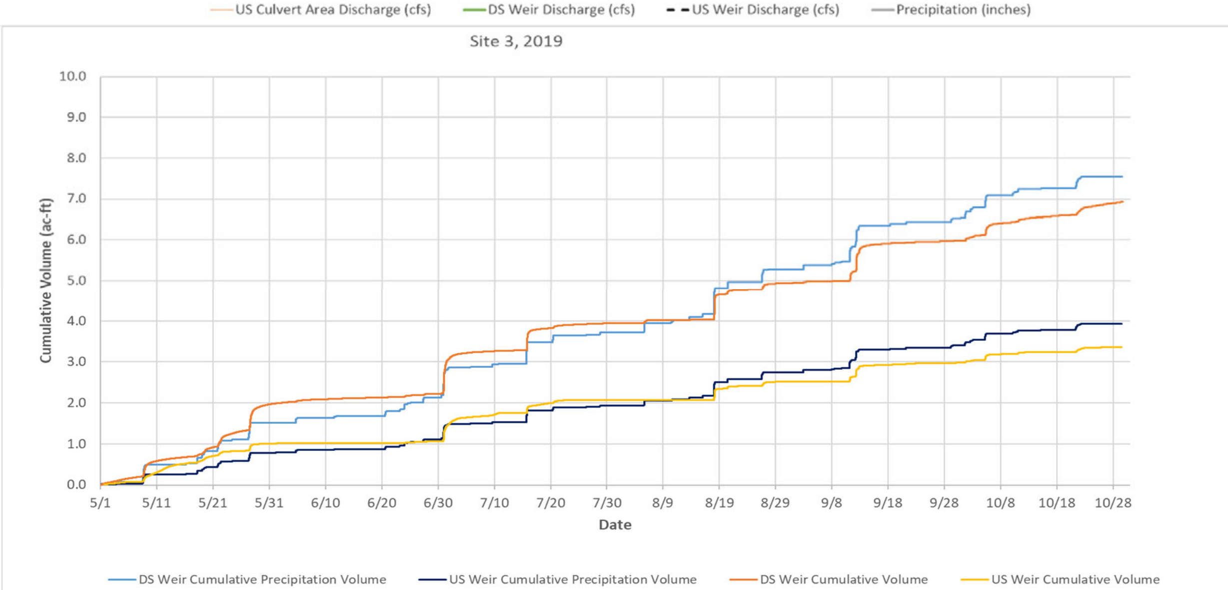


Figure 18: The event-based runoff ratios spanned a wide range, but the trendline for the events shows a moderate correlation with an R^2 of 0.60.

Site 3, 2019

A hydrograph and precipitation plot, a cumulative flow and precipitation volume plot, and tabulated seasonal flow, precipitation, and runoff and abstraction ratios for Site 3 in 2019 are shown in Figure 19.





				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed				
Site, Year	Start Date	End Date	Precip (inches)	Watershed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Watershed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Watershed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	**Abstraction Ratio**
3, 2019	5/1	10/29	26.3	1.79	3.36	3.93	**85%**	3.44	6.93	7.55	**92%**	1.65	3.57	3.62	**99%**	**1%**

Figure 19: Site 3, 2019 precipitation and hydrograph (top) result in the cumulative precipitation and flow plots (middle) and the seasonal runoff and infiltration tabulated data (bottom).

In 2019, the Site 3 study swale showed a seasonal runoff ratio of 99% with a corresponding abstraction ratio of 1%. This runoff ratio is outside the reference range and at the top end of the feasible range, assuming the project set up and analysis are valid. Potential reasons for this high runoff ratio are that

the study swale immediate watershed was underestimated, outside flow entered the watershed boundary, or that groundwater discharge was occurring within the project boundary.

Table 7: Twenty-one rainfall-runoff events were identified at Site 3 in 2019 ranging from one to 21 days in duration. The event-based runoff ratios varied from -5% to 144%.

				Upstream Weir		Downstream Weir		Study Swale Immediate Watershed					
Event	Start	Duration (days)	Event Precip (inches)	Precip volume (ac-ft)	Runoff Volume (ac-ft)	Precip volume (ac-ft)	Runoff Volume (ac-ft)	Precip volume (ac-ft)	Runoff Volume (ac-ft)	Abstraction Volume (ac-ft)	Abstraction Rate (in/hr)	**Runoff Ratio**	**Abstraction Ratio**
1	4/5/2019	2.0	0.56	0.08	0.00	0.16	0.08	0.08	0.08	0.00	0.00	**98%**	**2%**
2	4/11/2019	1.5	0.35	0.05	0.00	0.10	0.04	0.05	0.03	0.01	0.01	**69%**	**31%**
3	4/17/2019	1.2	0.85	0.13	0.15	0.24	0.30	0.12	0.15	-0.03	-0.02	**127%**	**-27%**
4	4/21/2019	3.0	0.22	0.03	0.07	0.06	0.12	0.03	0.04	-0.01	0.00	**148%**	**-48%**
5	4/29/2019	5.0	0.5	0.07	0.08	0.14	0.17	0.07	0.09	-0.02	0.00	**131%**	**-31%**
6	5/8/2019	2.0	1.47	0.22	0.17	0.42	0.35	0.20	0.18	0.02	0.01	**89%**	**11%**
7	5/15/2019	12.5	3.57	0.53	0.47	1.02	1.18	0.49	0.71	-0.22	-0.01	**144%**	**-44%**
8	6/4/2019	2.0	0.4	0.06	0.01	0.11	0.04	0.06	0.03	0.02	0.01	**57%**	**43%**
9	6/21/2019	21.0	4.01	0.60	0.72	1.15	1.13	0.55	0.41	0.14	0.00	**75%**	**25%**
10	7/15/2019	2.0	1.83	0.27	0.18	0.52	0.50	0.25	0.32	-0.07	-0.02	**126%**	**-26%**
11	7/19/2019	3.0	0.57	0.09	0.08	0.16	0.08	0.08	0.00	0.08	0.02	**-5%**	**105%**
12	7/28/2019	1.5	0.2	0.03	0.00	0.06	0.01	0.03	0.01	0.01	0.01	**46%**	**54%**
13	8/5/2019	2.0	0.8	0.12	0.00	0.23	0.07	0.11	0.07	0.04	0.01	**64%**	**36%**
14	8/17/2019	4.0	2.77	0.41	0.33	0.79	0.70	0.38	0.38	0.00	0.00	**99%**	**1%**
15	8/25/2019	4.0	1.11	0.17	0.10	0.32	0.16	0.15	0.06	0.09	0.01	**38%**	**62%**
16	9/1/2019	16.0	3.73	0.56	0.41	1.07	0.96	0.51	0.56	-0.04	0.00	**108%**	**-8%**
17	9/18/2019	1.0	0.12	0.02	0.01	0.03	0.01	0.02	0.00	0.02	0.01	**5%**	**95%**
18	9/21/2019	1.0	0.18	0.03	0.01	0.05	0.01	0.02	0.00	0.02	0.01	**9%**	**91%**
19	9/28/2019	9.0	2.28	0.34	0.21	0.65	0.43	0.31	0.22	0.09	0.01	**71%**	**29%**
20	10/9/2019	3.0	0.53	0.08	0.04	0.15	0.09	0.07	0.05	0.02	0.00	**74%**	**26%**
21	10/21/2019	3.0	1.03	0.15	0.10	0.30	0.20	0.14	0.10	0.04	0.01	**71%**	**29%**

The runoff ratio for individual storm events (Table 7) varied from -5% to 148%. The runoff ratio was generally higher earlier in the year, as would be expected with later season vegetative growth. The event-based rainfall-runoff relationship at this site and year was strong with an R^2 value of 0.87 (Figure 20). In addition to a seasonal trend, smaller rainfall events had smaller runoff ratios, which is expected based on hydrologic principles. Overall, the data from this site and year appears to some of the most precise from this project. However, the nearly 100% runoff ratio likely indicates problems with the accuracy or the analysis. Another implication of this data is to cast doubt on the 2018 data from this site. The variation in the seasonal runoff ratios between years seems unlikely. Since this year's data appears so precise, it seems likely that there is an error in the data collection or analysis for the 2018 data from this site.

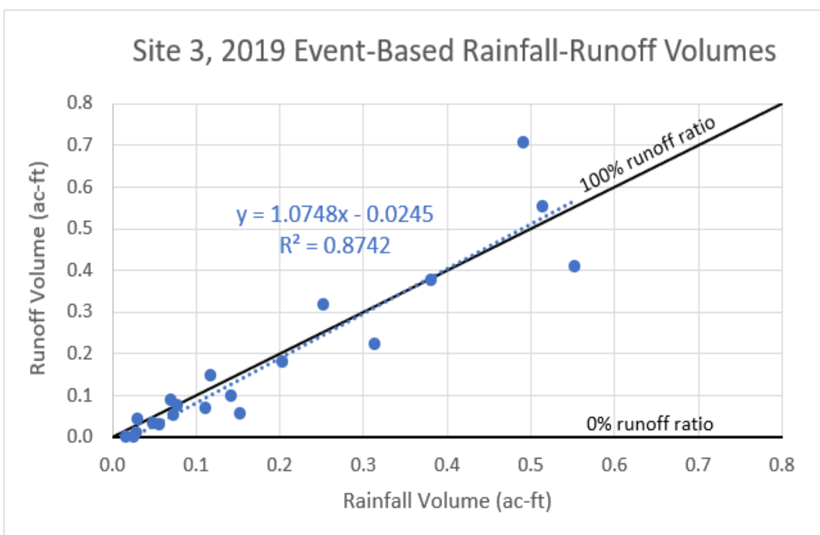
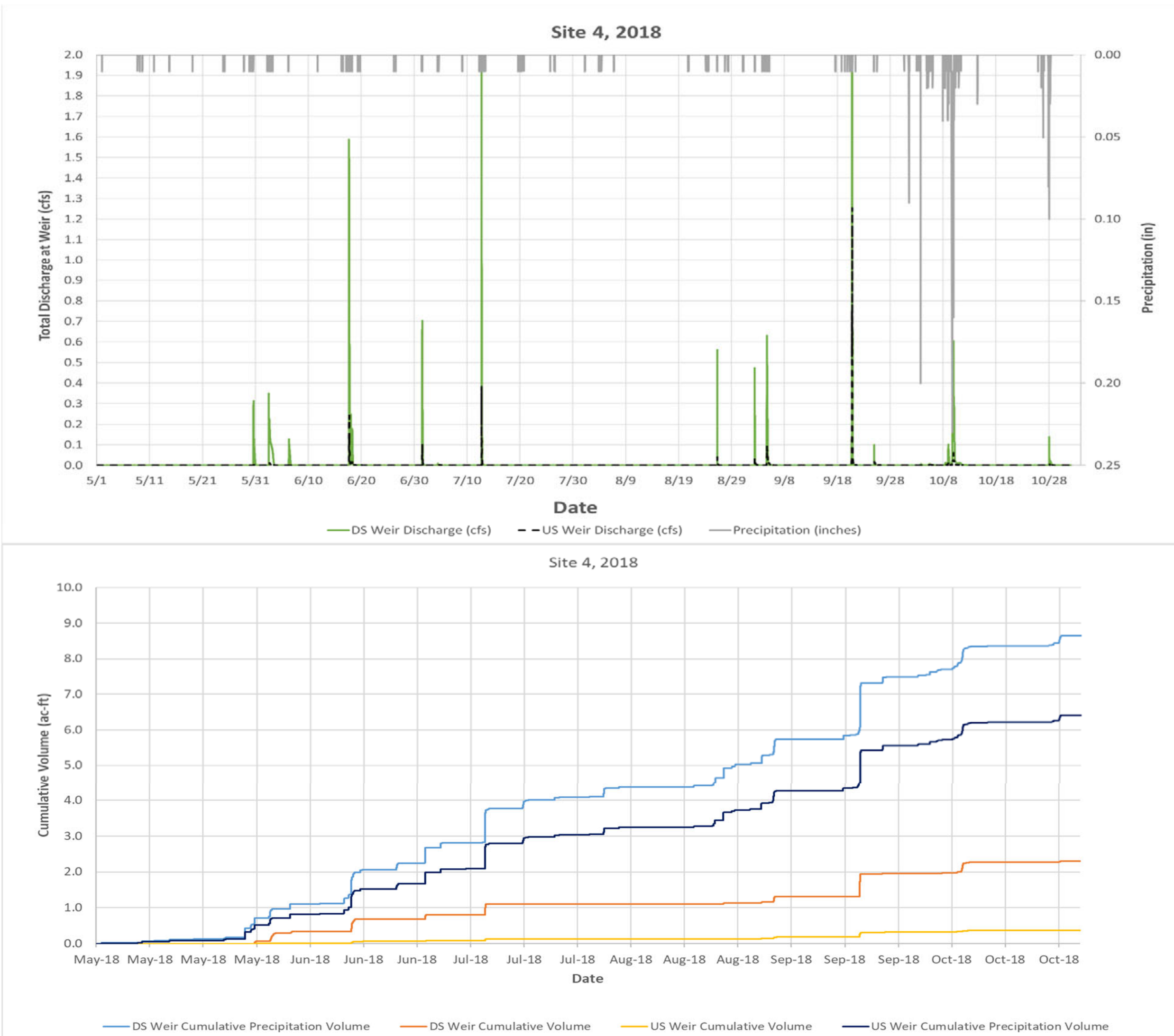


Figure 20: The event-based rainfall runoff trendline for the events shows a strong relationship with an R^2 of 0.87.

Site 4, 2018

A hydrograph and precipitation plot, a cumulative flow and precipitation volume plot, and tabulated seasonal flow, precipitation, and runoff and abstraction ratios for Site 4 in 2018 are shown in Figure 21.



				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed				
Site, Year	Start Date	End Date	Precip (inches)	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	**Abstraction Ratio**
4, 2018	5/1	11/1	23.6	3.26	0.37	6.42	**5.8%**	4.39	2.3	8.64	**27%**	1.13	1.93	2.22	**87%**	**13%**

Figure 21: Site 4, 2018 precipitation and hydrograph (top) result in the cumulative precipitation and flow plots (middle) and the seasonal runoff and infiltration tabulated data (bottom).

In 2018, the Site 4 study swale showed a seasonal runoff ratio of 87% with a corresponding abstraction ratio of 13%. This value is above the reference range. Potential reasons for this high runoff ratio are that the study swale immediate watershed was underestimated, outside flow entered the watershed boundary, or that groundwater discharge was occurring within the project boundary. The runoff ratio at the weirs (considering the upstream watershed) were 5.8% at the upstream weir and 27% at the downstream weir. The low number at the upstream weir may indicate that the upstream watershed is overestimated.

This event-based rainfall-runoff data range from -2% to 126% runoff ratio (Table 8). However, the first event of the season and mid-summer events (shown in grey) showed no or very little runoff while similar events before and after this did not. The reason for these low values may be that flow was circumventing the downstream weir or equipment errors during these times. Neglecting these events, the runoff ratios vary from 20-126%.

Table 8: Fifteen rainfall-runoff events were identified at Site 4 in 2018 ranging from 0.9 to 14.5 days in duration. The event-based runoff ratios varied from -26% to 102%. Events 6-11 (grey) showed no/very little runoff, which may have been due to downstream weir measurement error.

				Upstream Weir		Downstream Weir		Study Swale Immediate Watershed					
Event	Start	Duration (days)	Event Precip (inches)	Precip Volume (ac-ft)	Runoff Volume (ac-ft)	Precip Volume (ac-ft)	Runoff Volume (ac-ft)	Precip Volume (ac-ft)	Runoff Volume (ac-ft)	Abstraction Volume (ac-ft)	Abstraction Rate (in/hr)	**Runoff Ratio**	**Abstraction Ratio**
1	5/8/2018	0.9	0.14	0.04	0.00	0.05	0.00	0.01	0.00	0.01	0.01	**0%**	**100%**
2	5/28/2018	2.7	1.47	0.40	0.00	0.54	0.08	0.14	0.07	0.06	0.01	**53%**	**47%**
3	6/2/2018	1.8	0.71	0.19	0.00	0.26	0.06	0.07	0.06	0.01	0.00	**92%**	**8%**
4	6/5/2018	1.5	0.39	0.11	0.00	0.14	0.05	0.04	0.05	-0.01	0.00	**126%**	**-26%**
5	6/16/2018	4.7	2.56	0.70	0.05	0.94	0.35	0.24	0.30	-0.06	-0.01	**123%**	**-23%**
6	6/26/2018	1.5	0.51	0.14	0.00	0.19	0.00	0.05	0.00	0.05	0.02	**0%**	**100%**
7	7/1/2018	4.5	1.53	0.42	0.00	0.56	0.00	0.14	0.00	0.15	0.02	**-2%**	**102%**
8	7/12/2018	2.5	2.60	0.71	0.00	0.95	0.00	0.24	0.00	0.25	0.06	**-1%**	**101%**
9	7/19/2018	1.5	0.65	0.18	0.00	0.24	0.00	0.06	0.00	0.06	0.02	**0%**	**100%**
10	8/3/2018	1.0	0.63	0.17	0.00	0.23	0.00	0.06	0.00	0.06	0.04	**0%**	**100%**
11	8/24/2018	5.5	1.66	0.45	0.01	0.61	0.02	0.16	0.02	0.14	0.02	**11%**	**89%**
12	9/2/2018	4.0	1.87	0.51	0.04	0.68	0.15	0.18	0.11	0.07	0.01	**62%**	**38%**
13	9/17/2018	11.0	4.77	1.30	0.13	1.75	0.64	0.45	0.51	-0.06	0.00	**113%**	**-13%**
14	9/30/2018	14.5	2.41	0.65	0.05	0.88	0.32	0.23	0.27	-0.05	0.00	**121%**	**-21%**
15	10/25/2018	6.0	0.75	0.20	0.00	0.27	0.03	0.07	0.02	0.05	0.01	**30%**	**70%**

The event-based rainfall-runoff relationship at this site and year was moderate with an R^2 value of 0.70, but when the suspect events are removed, the R^2 value is substantially stronger at 0.94 (Figure 22). These R^2 values indicate good precision in this data. However, the very high runoff ratio could indicate problems with accuracy. One observable trend in these events is that larger events resulted in larger runoff ratios, which is expected based on hydrologic principles. A seasonal trend is not readily apparent as it was at other sites/years.

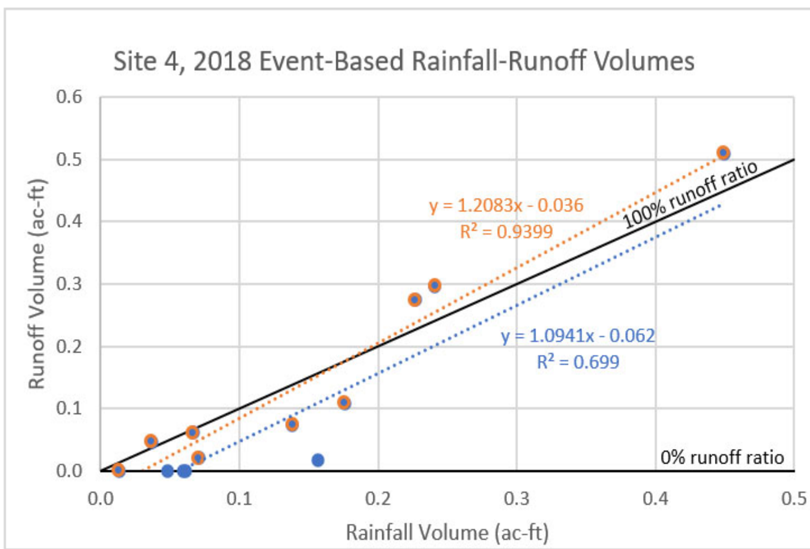
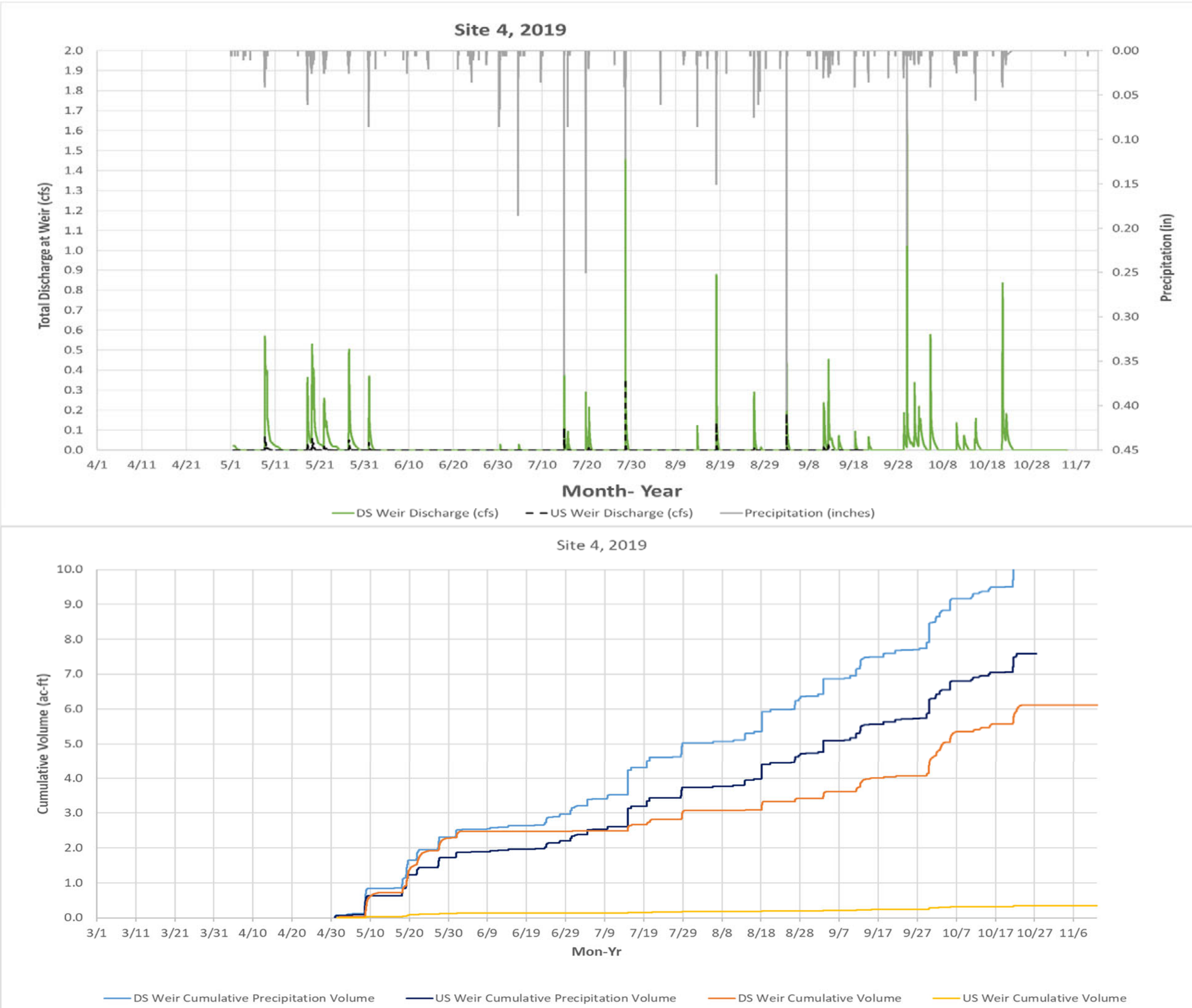


Figure 22: The R^2 value for linear trendline for the Site 4, 2018 event-based data is 0.70 when all data points (blue points) are considered and 0.94 when the mid-summer points where no/very little rain are removed (orange points).

Site 4, 2019

A hydrograph and precipitation plot, a cumulative flow and precipitation volume plot, and tabulated seasonal flow, precipitation, and runoff and abstraction ratios for Site 4 in 2019 are shown in Figure 23.



				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed				
Site, Year	Start Date	End Date	Precip (inches)	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	**Abstraction Ratio**
4, 2019	5/1	11/12	27.9	3.26	0.34	7.58	**4.5%**	4.39	6.12	10.2	**60%**	1.13	5.78	2.62	**221%**	**-121%**

Figure 23: Site 4, 2019 precipitation and hydrograph (top) result in the cumulative precipitation and flow plots (middle) and the seasonal runoff and infiltration tabulated data (bottom).

In 2019, the Site 4 study swale showed a seasonal runoff ratio of 221% with a corresponding abstraction ratio of -121%. This runoff ratio is substantially above the feasible and reference range. Considering the full contributing area, the upstream weir showed a runoff ratio of 4.5% while the downstream weir showed a runoff ratio of 60%. The amount of flow measured at the upstream weir appears very low, and possible reasons for the large seasonal runoff ratio are that flow was circumventing the upstream weir or equipment/measurement errors. The cumulative flow volume plot also shows how the downstream weir registered nearly all the precipitation volume until the end of May, then did not track flow during any June and early July events, and then again started tracking flow starting in Mid-July – this appears that there was weir measurement error through the first half of the year.

The runoff ratio for individual storm events in the study swale varied from 81% to 1962% (Table 9). This event-based rainfall-runoff relationship at this site and year was very weak with an R^2 value of 0.18 (Figure 24). Due to the number of issues with the data from this site and year, this should be considered very low confidence in the validity of the data.

Table 9: Twenty-one rainfall-runoff events were identified at Site 4 in 2019 ranging from 0.5 to 8.1 days.

				Upstream Weir		Downstream Weir		Study Swale Immediate Watershed					
Event	Start	Duration (days)	Event Precip (inches)	Precip Volume (ac-ft)	Runoff Volume (ac-ft)	Precip Volume (ac-ft)	Runoff Volume (ac-ft)	Precip Volume (ac-ft)	Runoff Volume (ac-ft)	Abstraction Volume (ac-ft)	Abstraction Rate (in/hr)	**Runoff Ratio**	**Abstraction Ratio**
1	4/12/19	1.0	0.29	0.079	0.000	0.106	0.260	0.027	0.260	-0.23	-0.14	**954%**	**-854%**
2	4/22/19	3.0	0.69	0.187	0.000	0.252	1.275	0.065	1.275	-1.21	-0.24	**1962%**	**-1862%**
3	5/8/19	2.5	1.99	0.541	0.038	0.728	0.621	0.187	0.583	-0.40	-0.10	**311%**	**-211%**
4	5/18/19	2.5	2.19	0.595	0.047	0.801	0.724	0.206	0.676	-0.47	-0.11	**328%**	**-228%**
5	5/21/19	2.0	0.80	0.217	0.016	0.293	0.352	0.075	0.336	-0.26	-0.08	**446%**	**-346%**
6	5/26/19	1.5	1.02	0.277	0.020	0.373	0.303	0.096	0.283	-0.19	-0.07	**295%**	**-195%**
7	5/31/19	1.5	0.56	0.152	0.009	0.205	0.183	0.053	0.173	-0.12	-0.05	**329%**	**-229%**
8	7/14/19	1.5	2.13	0.579	0.012	0.780	0.175	0.201	0.162	0.04	0.02	**81%**	**19%**
9	7/20/19	1.0	0.29	0.079	0.007	0.106	0.094	0.027	0.087	-0.06	-0.04	**320%**	**-220%**
10	7/28/19	1.5	1.06	0.288	0.021	0.388	0.252	0.100	0.231	-0.13	-0.05	**231%**	**-131%**
11	8/18/19	1.0	1.56	0.424	0.016	0.571	0.231	0.147	0.215	-0.07	-0.04	**146%**	**-46%**
12	8/18/19	8.1	0.71	0.193	0.003	0.260	0.085	0.067	0.082	-0.01	0.00	**122%**	**-22%**
13	9/11/19	2.5	1.42	0.386	0.016	0.519	0.351	0.134	0.335	-0.20	-0.05	**250%**	**-150%**
14	9/14/19	0.5	0.06	0.016	0.001	0.022	0.028	0.006	0.027	-0.02	-0.03	**475%**	**-375%**
15	9/27/19	4.3	2.12	0.575	0.050	0.774	0.576	0.199	0.526	-0.33	-0.05	**264%**	**-164%**
16	10/1/19	2.7	0.92	0.250	0.013	0.337	0.404	0.087	0.391	-0.30	-0.07	**452%**	**-352%**
17	10/5/19	1.5	0.92	0.250	0.012	0.337	0.274	0.087	0.262	-0.18	-0.07	**303%**	**-203%**
18	10/11/19	1.0	0.24	0.065	0.001	0.088	0.069	0.023	0.067	-0.04	-0.03	**298%**	**-198%**
19	10/12/19	1.3	0.17	0.046	0.001	0.062	0.053	0.016	0.052	-0.04	-0.02	**324%**	**-224%**
20	10/15/19	1.0	0.34	0.092	0.003	0.124	0.089	0.032	0.086	-0.05	-0.03	**268%**	**-168%**
21	10/20/19	3.6	1.91	0.519	0.024	0.699	0.525	0.180	0.501	-0.32	-0.05	**278%**	**-178%**

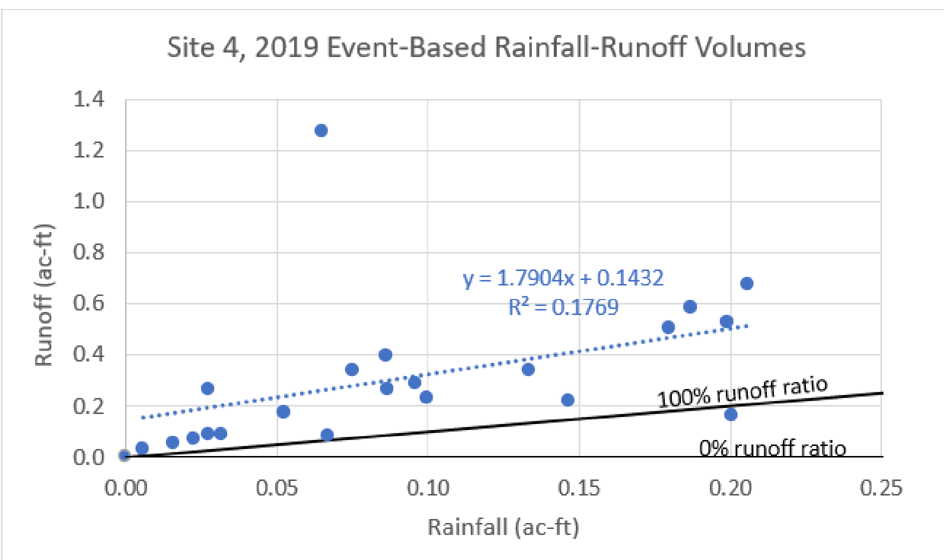
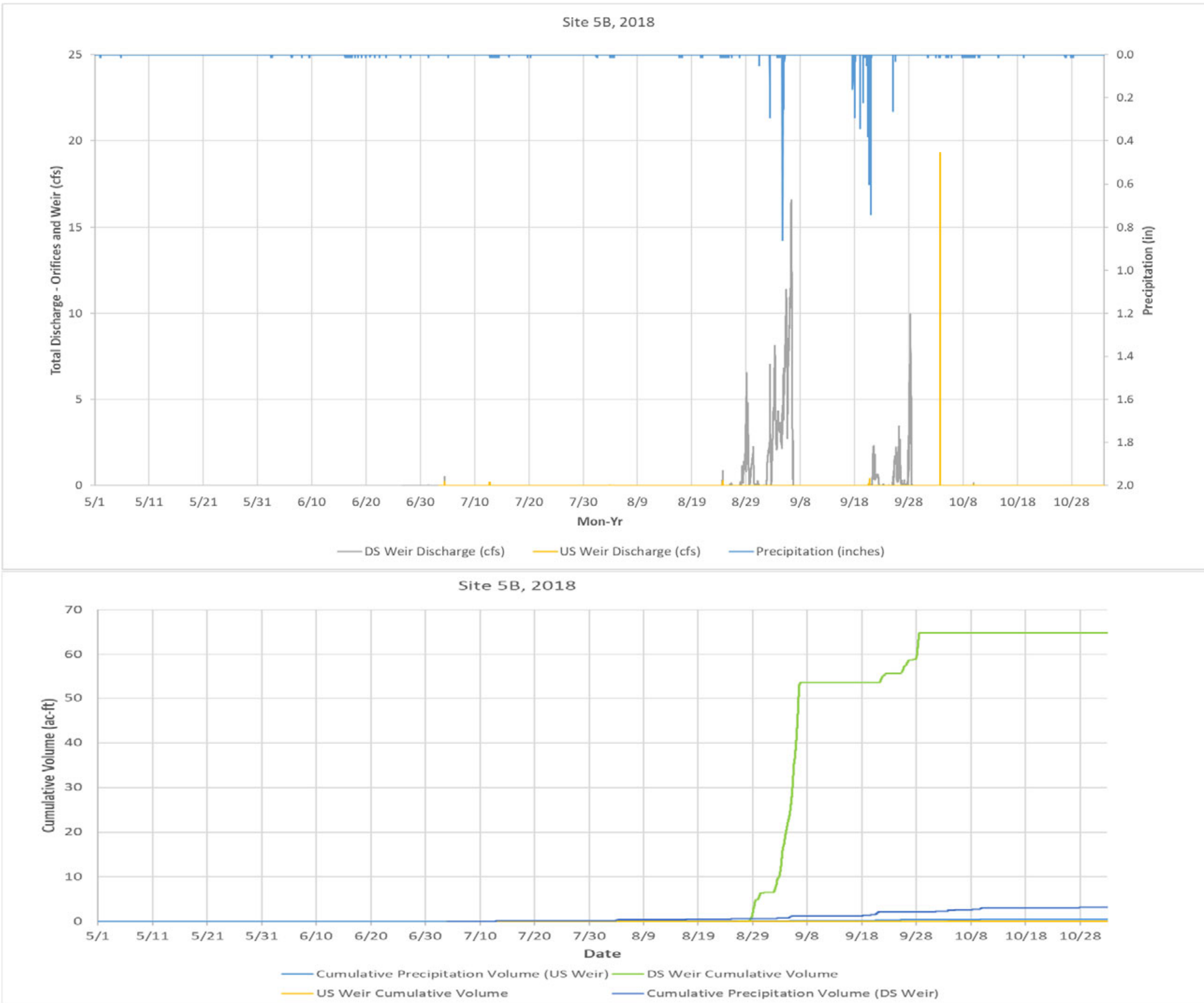


Figure 24: The event-based rainfall runoff trendline for Site 4 in 2019 shows a weak relationship with an R^2 of 0.18.

Site 5B, 2018

A hydrograph and precipitation plot, a cumulative flow and precipitation volume plot, and tabulated seasonal flow, precipitation, and runoff and abstraction ratios for Site 5B in 2018 are shown in Figure 25.



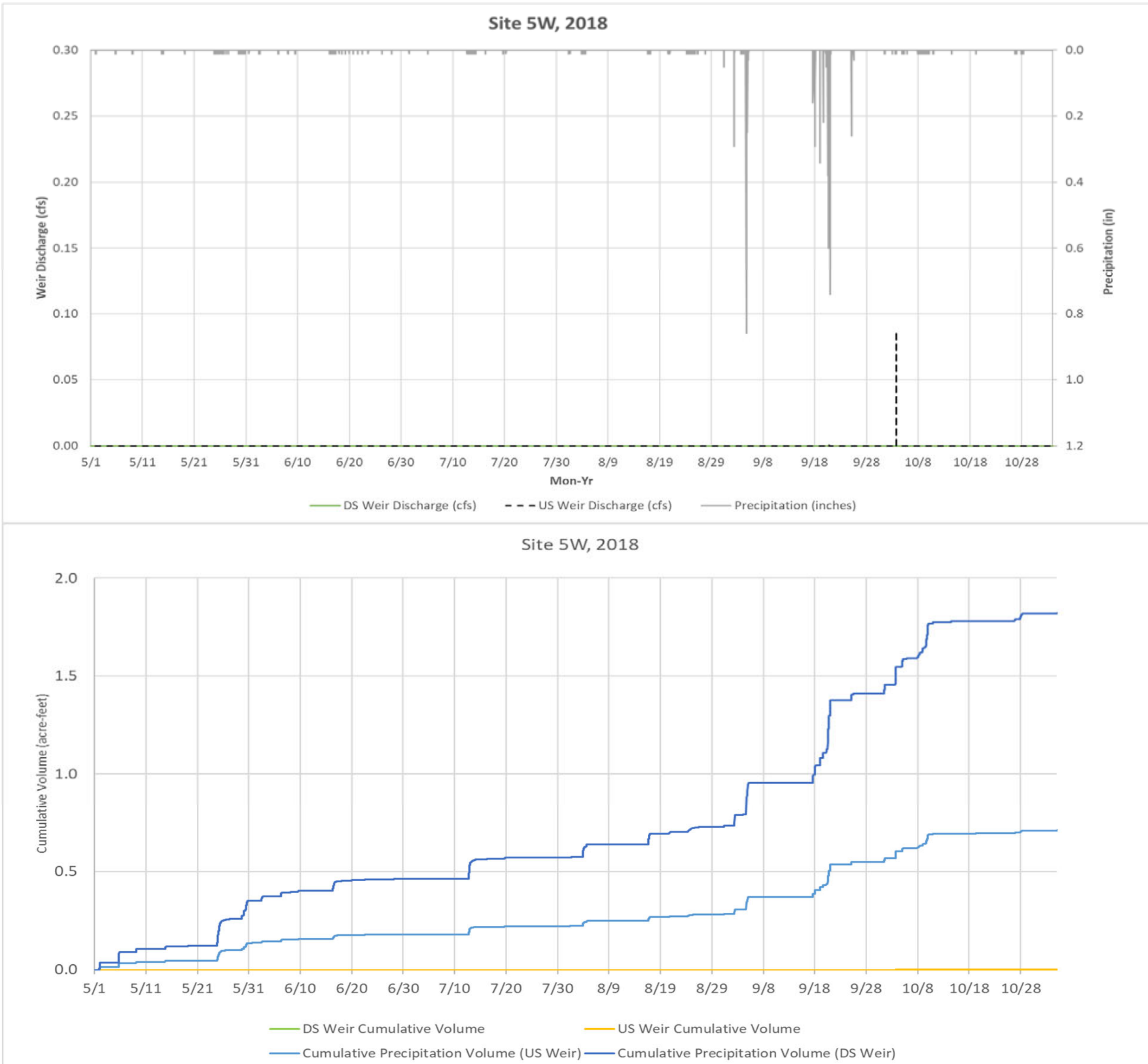
				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed				
Site, Year	Start Date	End Date	Precip (inches)	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	**Abstraction Ratio**
5B, 2018	7/4	11/1	12.5	0.53	0.14	0.55	**25.5%**	3.10	64.83	3.22	**2013%**	2.57	64.69	2.67	**2423%**	**-2323%**

Figure 25: Site 5B, 2018 precipitation and hydrograph (top) result in the cumulative precipitation and flow plots (middle) and the seasonal runoff and infiltration tabulated data (bottom).

The data for Site 5B in 2018 shows serious errors in that substantially more flow was measured than precipitation occurred. Furthermore, the measured seasonal precipitation is suspiciously low, indicating potential issues with measurement. These data were deemed sufficiently flawed that further analysis was not completed.

Site 5W, 2018

A hydrograph and precipitation plot, a cumulative flow and precipitation volume plot, and tabulated seasonal flow, precipitation, and runoff and abstraction ratios for Site 5W in 2018 are shown in Figure 26.



				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed				
Site, Year	Start Date	End Date	Precip (inches)	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	**Runoff Ratio**	**Abstraction Ratio**
5W, 2018	5/1	11/1	16.7	0.51	0.00	0.71	**0.1%**	1.31	0.00	1.82	**0.0%**	0.8	0.00	1.11	**0%**	**100%**

Figure 26: Site 5W, 2018 precipitation and hydrograph (top) result in the cumulative precipitation and flow plots (middle) and the seasonal runoff and infiltration tabulated data (bottom).

The data for Site 5W in 2018 show serious errors in that no flow was measured. These data were deemed sufficiently flawed that further analysis was not done.

Water Budget Application Summary

The precipitation and runoff seasonal totals as well as the runoff and abstraction ratios for all analyzed sites and years are shown in Table 10.

Table 10: The seasonal runoff and abstraction ratios vary substantially, several being well beyond the feasible range (feasibible range assumes that the assumptions and application of the project are valid). This variation indicates errors in the assumptions, data collection, or analysis.

				Upstream Weir				Downstream Weir				Study Swale Immediate Watershed					
Site, Year	Start Date	End Date	Precip (inches)	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	Runoff Ratio	Water-shed (acres)	Flow Volume (acre-ft)	Precip Volume (acre-ft)	Runoff Ratio	Water-shed (acres)	Precip Volume (acre-ft)	Runoff Volume (acre-ft)	Abstraction Volume (acre-ft)	**Runoff Ratio**	**Abstract-ion Ratio**
1, 2018	5/20	11/1	20.1	176.06	2.12	294.31	0.7%	176.82	2.32	295.58	0.8%	0.76	1.27	0.19	1.08	**15%**	**85%**
1, 2019	5/1	10/30	30.0	176.06	16.71	440.30	3.8%	176.82	6.70	442.20	1.5%	0.76	1.90	-10.01	11.91	**-527%**	**627%**
2, 2018	9/1	11/1	8.1	N/A				represented in info at right				0.64	0.43	1.00	-0.57	**233%**	**-133%**
3, 2018	4/28	11/1	26.9	1.79	1.33	4.02	33%	3.44	3.06	7.73	40%	1.65	3.71	1.73	1.98	**47%**	**53%**
3, 2019	5/1	10/29	26.3	1.79	3.36	3.93	85%	3.44	6.93	7.55	92%	1.65	3.62	3.57	0.05	**99%**	**1%**
4, 2018	5/1	11/1	23.6	3.26	0.37	6.42	5.8%	4.39	2.3	8.64	27%	1.13	2.22	1.93	0.29	**87%**	**13%**
4, 2019	5/1	11/12	27.9	3.26	0.34	7.58	4.5%	4.39	6.12	10.2	60%	1.13	2.62	5.78	-3.16	**221%**	**-121%**
5B, 2018	7/4	11/1	12.5	0.53	0.14	0.55	25.5%	3.10	64.83	3.22	2013%	2.57	2.67	64.69	-62.02	**2423%**	**-2323%**
5W, 2018	5/1	11/1	16.7	0.51	0.00	0.71	0.1%	1.31	0.00	1.82	0.0%	0.8	1.11	0.00	1.11	**0%**	**100%**

The event-based rainfall-runoff analysis for Sites 1, 3, and 4 (the data sets deemed usable for completing analysis but of any level confidence in the data validity) are shown in Figure 27.

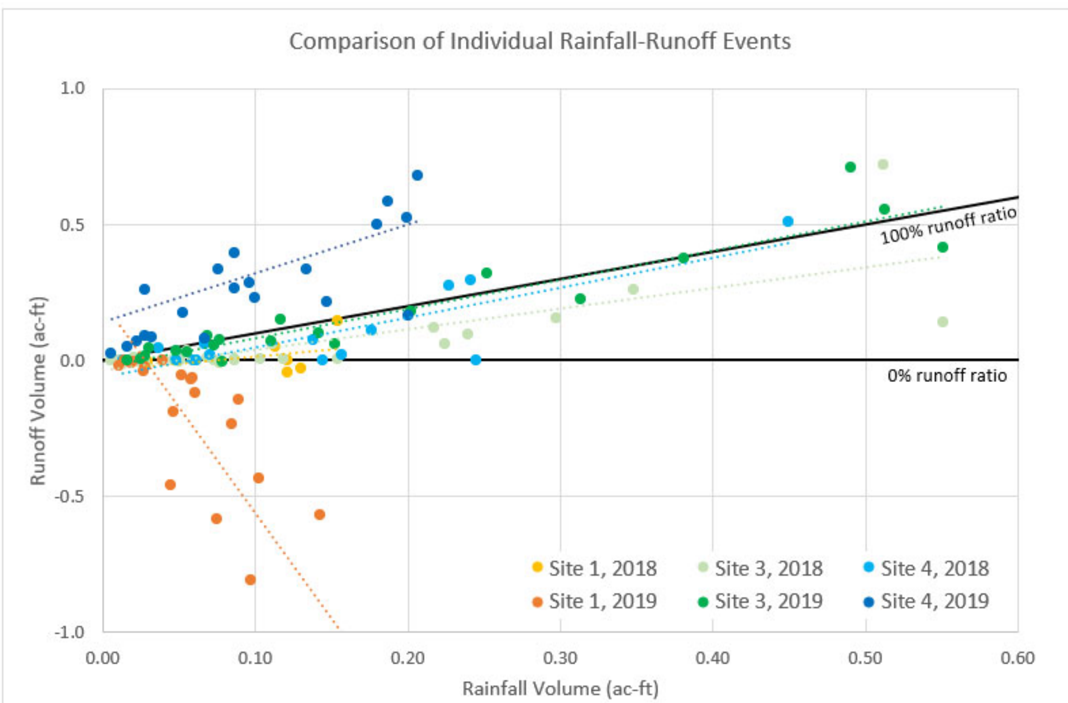


Figure 27: The event-based runoff ratios for each year and site illustrate where the individual events fall compared to the 0% and 100% runoff ratios (i.e. the feasible range if the application is valid). While the runoff ratios vary substantially between events at the same site, some trends can be seen at each site.

Abstraction rates for rainfall-runoff events for Sites 1, 3, and 4 are shown in Figure 28. As would be expected with low abstraction ratios, the calculated abstraction rates at the two highest confidence data sets (Site 3, 2019 and Site 4, 2018) are very low, generally in the 0-0.5 in/hour range. While abstraction rates are shown below for all usable data sets for comparison, Site 1, 2019 and Site 4, 2019 clearly showed substantial issues with data and should not be considered valid.

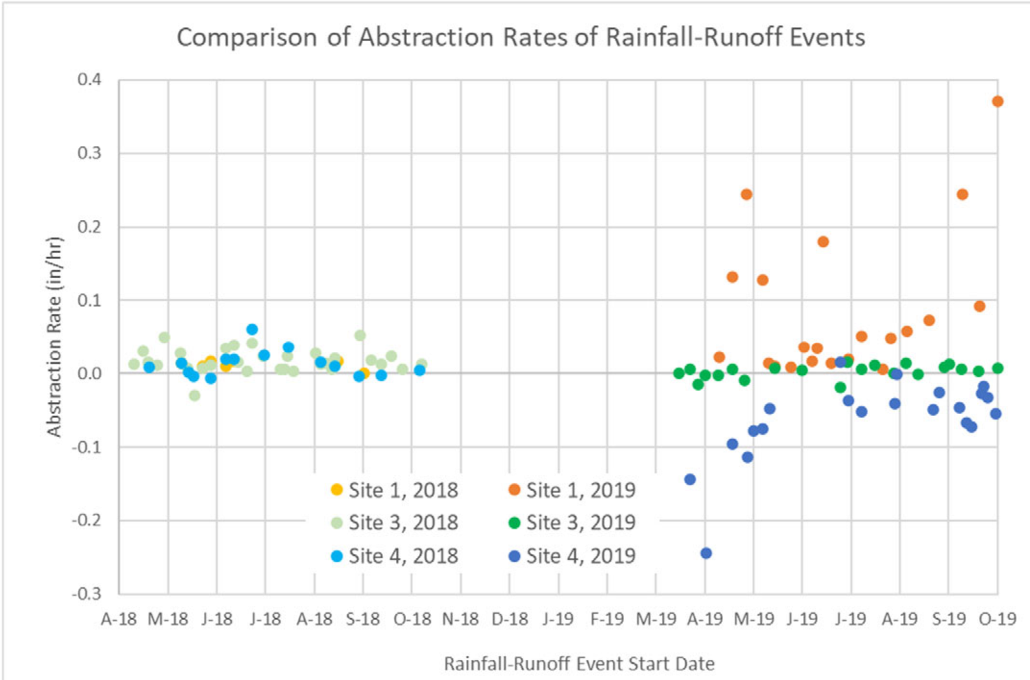


Figure 28: Abstraction rates were calculated for rainfall-runoff events at sites 1, 3, and 4. Abstraction rates for the highest confidence data sets (Site 3, 2019 and Site 4, 2018) were generally in the 0 to 0.05 inch per hour range.

The abstraction rates apply to the pervious portion of the study swale watershed, over the full duration of rainfall-runoff events. As such, these abstraction rates should not be construed as swale infiltration rates. In order to estimate the swale (only) infiltration rates, the swale would need to be isolated so that no runoff (other than the measured channel inflow and outflow) would be entering the swale boundary, and the only the area of the swale would be used to calculate the infiltration rate. Furthermore, the rainfall-runoff event duration may not be the most appropriate time scale to calculate an infiltration rate. Instead, the author would recommend assessing infiltration rates over varying time steps (i.e. one hour, two hour, five hour, etc.) and plotting those calculated infiltration rates against time to determine the most appropriate time step. Flow and precipitation data should be stored, corrected, analyzed, and additional calculations should be completed in a robust continuous data database and not in excel to make data, corrections, calculations, and field notes readily integratable.

A summary of runoff ratios, confidence in the data validity, and the author's suspected issues with the data for each site and year are shown in Table 11. These suspected issues were developed by the author based on the characteristics of the data, applying prior experience with continuous data collection and analysis as well as experience working with water budgets and runoff ratios. While the author identified these suspected issues based on the characteristics of the data, the original project team also reported specific issues that would contribute to errors in the data or application (see Appendix A). These issues are generally consistent with the author's suspected issues of the data and illustrate specific examples of the suspected issues. Unfortunately, because the continuous data and any data corrections or adjustments are not readily available within the datasets available to the author (i.e. data is stored in excel with no traceable notes and corrections versus being stored in a robust continuous data database), there is no way to ensure the data was corrected where possible, and in other cases, there is no technically supported method to correct for identified issues. This specific gap in the project further contributed to lower confidence on the validity of the project data.

Table 11: The seasonal and event-based runoff ratios varied substantially between sites and years, and several runoff ratios are outside of the feasible range. The R^2 value from the event-based runoff ratio analysis can be used to compare how well these events showed a trend in similar runoff ratios. Generally, the confidence and usability of these project data are low. The two data sets with the highest confidence show nearly 100% runoff, which is substantially above the reference range. The suspected issues and notes as discussed within this section are summarized for comparison.

Site, Year	Rainfall Runoff Events	Seasonal Runoff Ratio	Range in Event Runoff Ratios	Event Trendline R^2 Value	Confidence in Data Validity/ Usability	Suspected Issues Based on Data Characteristics & Notes
1, 2018	7	15%	-38% to 95%	0.16	Very Low	Flow circumventing downstream weir or monitoring equipment early in season and/or instrumentation/analysis errors. Overestimated upstream watershed strongly suspected.
1, 2019	22	-527%	-1023% to 627%	0.89	Very Low	Flow circumventing downstream weir or monitoring equipment through the entire season and/or instrumentation/analysis errors causing all negative runoff ratios, overestimated upstream watershed. Upstream weir data might be usable if upstream watershed or contributing area could be verified.
3, 2018	31	47%	-16% to 140%	0.60	Low	Higher runoff early in season may be vegetation or groundwater influence, or flow circumventing the weir or monitoring equipment. Substantially different runoff ratios than the 2019 data at this site makes more suspect.
3, 2019	21	99%	-5% to 148%	0.87	Low-Moderate	Study swale immediate watershed was underestimated, outside flow entered the watershed boundary, or groundwater discharge was occurring within the project boundary.
4, 2018	15 (9*)	87%	-26% to 102%	0.70 (0.94*)	Low-Moderate	Flow circumventing downstream weir or monitoring equipment mid-Summer, study swale immediate watershed was underestimated, outside flow entered the watershed boundary, or groundwater discharge was occurring within the project boundary. * = mid summer data removed so runoff ratios vary from 20-126% and confidence increases.
4, 2019	21	221%	81% to 1962%	0.18	Very Low	Flow circumventing downstream weir or monitoring equipment
2, 2018	3	233%	-93% to 190%	0.40	Unusable	Equipment or site malfunction
5B, 2018	Not analyzed due to severe data issues				Unusable	Equipment or site malfunction
5W, 2018					Unusable	Equipment or site malfunction

Modeling

The second objective of this study was to model volume removal (abstraction) using the MPCA MIDS Calculator, UMN Dry Swale Calculator, and XPSWMM and compare the estimated abstraction to the in-field measured abstraction.

MIDS Calculator

The MPCA MIDS calculator estimates the pollutant and runoff volume removal of several best management practices (BMPs) including swales and swale side slopes. Annual runoff volumes are calculated using the Simple Method, and annual volume reductions were developed using P8 Urban Catchment Model developed performance curves. Detailed documentation is included in the Minnesota Stormwater Manual MIDS calculator documentation and Performance curves for MIDS calculator.

Sites 3 and 4 were represented in the MPCA MIDS Calculator to the extent possible based on the MN Stormwater Manual's MIDS directions for using swale side slope as a BMP in the MIDS calculator and using swale without an underdrain as a BMP in the MIDS calculator. The soils were represented as HSG B soils infiltration rates at Site 3 and Site HSG C soils infiltraiton rates at Site 4 because 1) the actual soils identified at the sites are HSG D soils, which cannot be represented in MIDS, and 2) these were the preliminary HSG assessment by the original porject team (which were later corrected), and 3) XPSWMM modeling assumed HSG B soils for both sites.

Four MIDS calculator scenarios were developed for each site to show how inclusion or exclusion of the swale watershed affects the runoff volume reduction results. Scenarios 1-3 are useful to observe how the modeled system reacts to adding watershed area/swale components, but only Scenario 4 complies with the MIDS calculator guidance, because the entire upstream watershed and all swale components are included. Specifically, Sites 3 and 4 follow the Scenario B layout from the instructions, which require inclusion of immediate and upstream watershed.

The four MIDS scenarios modeled for each Sites 3 and 4 were:

1) the roadside swale slope of the immediate swale study area
2) both the grass-side and roadside swale slopes of the immediate study swale (adding in the grass-side to scenario 1)
3) the study swale watershed with runoff routed down the swale length (same as scenario 2 but adding the swale channel length)
4) the whole upstream and study swale watershed (same as scenario 3 but adding in the upstream area)

Summarized MIDS calculator output for Site 3 and Site 4 are shown in Table 12, and full calculator inputs are included in Appendix B. Site 3, Scenario 4 (representing the full contributing area and using HSG B soils) removed 36% of the annual runoff, meeting 17% of the performance goal. Site 4, Scenario 4 (representing the full contributing area and using HSG C soils), removed 25% of the annual runoff, meeting 20% of the performance goal.

Depending on the scenario (i.e. how much of the watershed was represented), the amount of runoff reduction varied substantially: from 10-61% for Site 3 and from 0-42% for Site 4. These results illustrate the importance of representing the whole swale watershed in order to estimate runoff reduction. If runoff is routed only down the side slopes (and not down the swale channel, Scenarios 1 and 2), the modeled amount of removed runoff is relatively small, as can be seen between Scenarios 2 and 3, where

removed runoff increases from 13% to 61% for Site 3 and from 0% to 32% for Site 4. The swale side slope is steep and short compared to the swale channel, allowing a longer contact time and more abstraction to occur in the swale channel than in the swale side slope.

Table 12: Four MIDS calculator scenarios were developed representing each Site 3 and Site 4. The (event-based) portion of the performance goal retained and the removed portion of the annual runoff are the two key outputs, highlighted in yellow.

Site		Scenario 1: Roadside Only of Study Swale Immediate Watershed (road & shoulder/swale side slope using side slope BMP only)	Scenario 2: Roadside and Grassside of Study Swale Immediate Watershed (scenario 1 adding in grass side slope, using side slope BMP only)	Scenario 3: Immediate Study Swale Watershed and Swale (same as 2 but then route swale side slopes to swale channel)	Scenario 4: Study Swale Full Watershed (Scenario 3 and adding in upstream acres).
Site 3	Performance Goal (inches from imp acres)	1	1	1	1
Site 3	Performance Volume Goal (ac-in)	0.216	0.216	0.216	0.876
Site 3	Volume Removed by BMPs (inches from imp acres)	0.03	0.03	0.56	0.17
Site 3	Performance Goal Retained	3%	3%	56%	17%
Site 3	Annual Runoff (inches from total area)	12.7	9.3	9.3	10.5
Site 3	Annual Runoff Volume (ac-in)	7.5	10.2	10.2	35.9
Site 3	Annual Runoff Volume Removed by BMPs (inches)	1.5	1.2	5.7	3.7
Site 3	Removed Portion of Annual Runoff	10%	13%	61%	36%
Site 4	Performance Goal (inches from imp acres)	1	1	1	1
Site 4	Performance Volume Goal (ac-in)	0.306	0.306	0.306	0.625
Site 4	Volume Removed by BMPs (inches from imp acres)	0.0009	0.0009	0.32	0.20
Site 4	Performance Goal Retained	0%	0%	32%	20%
Site 4	Annual Runoff (inches from total area)	13.5	11.5	11.5	8.9
Site 4	Annual Runoff Volume (ac-in)	11.2	13.0	13.0	39.0
Site 4	Annual Runoff Volume Removed by BMPs (inches)	0.06	0.08	4.8	2.2
Site 4	Removed Portion of Annual Runoff	0%	1%	42%	25%

Comparing Scenario 3 to Scenario 4, the performance volume goal increases due to the inclusion of the upstream watershed, which appears to include the upstream impervious area in the performance goal calculation. The result of including the upstream watershed is that the removed portion of runoff decreases from 61% to 36% at Site 3 and from 42% to 25% at Site 4. This decrease in percent removal actually represents an increase in the volume removed; however, the total runoff is substantially increased as well, hence the decreasing percent removal. This decrease in effectiveness can be explained by the swale's abstraction capacity being overwhelmed by the upstream contributing area runoff.

Relative to this study, three limitations of the MIDS calculator were identified. 1) The lowest k_{sat} value that can be used in the swale channel is 0.2 inch per hour. 2) Effects of high water table and/or confining layers cannot be represented. 3) Any upstream impervious area is included in the performance goal calculation, although it may not be needed to assess the compliance to the CSW Permit.

UMN Dry Swale Calculator

The UMN Minnesota Dry Swale Calculator estimates the portion of annual precipitation from the road and roadside swale that is infiltrated in the swale and side slopes. The Calculator was developed based on the MNDOT-sponsored UMN study: Enhancement and Application of the Minnesota Dry Swale Calculator. The calculator uses infiltration performance curves developed through Green Ampt modeled infiltration. The calculator was validated using saturated soil conductivity measurements and simulated rainfall events.

Sites 3 and 4 were represented in the UMN Dry Swale Calculator to the extent possible based on the instructions and inputs of the calculator. The soils were represented as HSG B soils infiltration rates at Site 3 and Site HSG C soils infiltraiton rates at Site 4 (same as the MIDS Calculator applications). To investigate the lower and upper estimate limits of the UMN Dry Swale calculator, the lowest and highest possible infiltration scenarios were developed by adjusting the width ratio and k_{sat} to their lowest and then highest possible values.

The UMN Dry Swale Calculator input and output for the Site 3 and 4 applications are shown in Table 13. The infiltrated portion of annual rainfall was estimated to be 69% at Site 3 and 54% at Site 4. The extreme cases in the calcualtor resulted in a low of 8% and a high of 99% of annual rainfall infiltrated.

Table 13: Sites 3 and 4 were simulated to the ability possible based on the calculator's inputs. The calculator's output is the annual infiltrated rainfall (that fell on the road surface). The lowest and highest possible outputs were also identified based on the upper and lower limits built into the calculator of the swale to road ratio and k_{sat} values.

	Site 3	Site 4	Lowest Possible Value	Highest Possible Value
Location	Minneapolis/St. Paul			
ksat (in/hr)	0.45	0.2	0.06	6.30
Road Width (m)	7.5	5.1	10	10
Side Slope Width (m)	8.1	5.9	1	14
Ws/Wr	1.08	1.16	0.1	1.4
Annual Infiltrated Rainfall	69%	54%	8%	99%

Relative to this study, some limitations of the UMN Swale calculator were identified. Similarly to the MIDS calculator, 0.2 inch per hour is the lowest k_{sat} value that can be represented, and high ground water or impervious layers cannot be represented. Additional limitations of the UMN Swale Calcultor are that the upsream contributing area of the swale is not considered, and the slope of the swale channel cannot be adjusted. Finally, the output term of the calculator is not the same as the CSW Permit requirements. This brief review of limitations did not include a deeper review of calculation methods.

XPSWMM Model

XPSWMM is a more sophisticated computer model compared to the MIDS and UMN Calculators, specifically geared to model complex stormwater applications. The model uses a number of hydrologic and hydraulic numeric models. Detailed information is available from the model developer Innovyze.

Sites 3 and 4 were modeled using XPSWMM to estimate runoff and abstraction ratios to compare to the field study. The methods and results of the XPSWMM modeling effort by Barr Engineering are included in Appendix H. These sites were both modeled as HSG B soils using the land use breakdowns in the Site Selection and Characterization section. XPSWMM model results are shown in shown in Table 14.

At Site 3, this model estimated 8% and 14% seasonal runoff ratio for 2018 and 2019, respectively, corresponding to a 92% and 86% abstraction ratio. At Site 4, the model estimated 5% and 10% seasonal runoff ratio for 2018 and 2019, respectively, corresponding to a 95% and 90% abstraction ratio.

Table 14: Site 3 and Site 4 were modeled to simulate the precipitation conditions observed in 2018 and 2019. Generally, the model produced very low runoff ratios, ranging from 5% to 14% over the two sites and years.

	Precip	Infiltration		Evapotranspiration		Abstraction		Runoff	
	(inches)	(inches)	(ratio)	(inches)	(ratio)	(inches)	(ratio)	(inches)	(ratio)
Site 3, 2018	19.53	13.29	68%	4.69	24%	17.98	92%	1.55	8%
Site 3, 2019	26.32	20.65	78%	1.89	7%	22.54	86%	3.78	14%
Site 4, 2018	17.6	12.81	73%	3.95	22%	16.76	95%	0.84	5%
Site 4, 2019	20.7	17.72	86%	0.85	4%	18.57	90%	2.13	10%

Modeling Comparison and Discussion

A comparison of the MPCA MIDS Calculator and UMN MN Dry Swale Calculator inputs and outputs is shown in Table 15. While a detailed comparison of the calculation methods of these models is outside the scope of this project, a primary difference between the calculators is that the UMN Calculator does not consider the upstream watershed nor the specific dimension and size of the swale.

Table 15: The MPCA MIDS Calculator the UMN Dry Swale Calculator are two tools used in this study to estimate the percentage of annual rainfall that is abstracted in a swale and swale side slope. The MPCA MIDS calculator includes more inputs than the UMN Dry Swale Calculator.

	MPCA MIDS Calculator (swale side slope and swale)	UMN Dry Swale Calculator
Input	• MN zip code (for annual rainfall depth) • Infiltration rate of most restrictive soil layer within five feet of bottom of practice • Swale geometry include dimensions and slope of swale channel bottom and sides. • Areas and types of landcover in immediate swale area • Upstream/contributing watershed • Stormwater routing through other BMPs (if applicable)	• MN regional city (for rainfall distribution) • k_{sat} of swale side slope • Ratio of swale width to road width
Output	• % of CSW permit performance goal retained • % of annual runoff from the swale watershed that is abstracted by the swale and swale side slope	• % of annual rainfall on the road and side slope infiltrated by the swale and swale side slope

To make the output terms of the multiple models comparable, approximations and calculations were developed to transform the output terms of each model to equivalent terms. The output units of the MIDS calculator and the UMN Dry Swale Calculator are both percentage; however, upon closer examination, the parameters used to create these percentages are different. Table 16 shows the models' result terms and the transformations used to develop the equivalent term for each model output. The red numbers indicate which of the below listed approximations and calculations were applied.

Table 16: The field study, XPSWMM model, MIDS Calculator, and the UMN Calculator each produce a different result term. Using assumptions and calculations presented in the below list (reference number shown in red font), the results are transformed into the same terms as the field study: the abstraction ratio - the portion of the rainfall that is abstracted within the swale.

Method	Result Term	Symbol	Translating Calculations	Equivalent Term
Field Study	$\frac{\text{abstraction volume in swale watershed}}{\text{rainfall volume in swale watershed}}$	$= \frac{A_{sw}}{P_{sw}}$		$\approx_{1} \frac{A_{bmp}}{P_{sw}}$
SWMM	$\frac{\text{abstraction volume in swale watershed}}{\text{rainfall volume in swale watershed}}$	$= \frac{I_{sw}+ET_{sw}}{P_{sw}}$		$\approx_{2} \frac{A_{bmp}}{P_{sw}}$
MIDS	$\frac{\text{abstraction volume of swale and side slope}}{\text{runoff volume from swale watershed (into the swale)}}$	$= \frac{A_{s+ss}}{RO_{sw}}$	$\approx_{3} \frac{A_{bmp}}{RO_{sw}} *_{4} \frac{RO_{sw}}{P_{sw}}$	$= \frac{A_{bmp}}{P_{sw}}$
UMN	$\frac{\text{infiltration volume of swale and swale side slope}}{\text{rainfall volume in partial swale watershed (road \& swale slope)}}$	$= \frac{I_{s+ss}}{P_{pw}}$	$\approx_{5} \frac{A_{bmp}}{P_{pw}} *_{6} \frac{A_{pw}}{A_{sw}}$	$= \frac{A_{bmp}}{P_{sw}}$

Where:

A_{sw} = abstraction volume in the swale watershed
I_{sw} = infiltration volume in swale watershed
I_{ss} = infiltration volume of swale side slope
I_{s+ss} = infiltration volume of swale bottom and swale side slope
I_{bmp} = infiltration volume of the BMP under consideration
RO_{sw} = runoff volume from swale watershed into the swale
P_{sw} = rainfall volume in swale watershed
P_{pw} = rainfall volume in partial swale watershed (road & swale slope)
A_{pw} = area of partial watershed under consideration
A_{sw} = area of swale watershed

Specific approximations and calculations used as numbered in Table 16:

1. Abstraction within the swale alone could not be separated from the abstraction within the immediate study swale watershed. Therefore, all field study abstraction is credited to the BMP.
2. XPSWMM estimated the infiltration and evapotranspiration occurring in the immediate study swale watershed and did not differentiate a separate swale area, which is credited as BMP abstraction.
3. The MIDS calculator gives the annual runoff removed by the swale and swale side slope, which is the abstraction in the BMP.
4. As previously defined Equation 4, the runoff ratio is the volume of runoff divided by the volume of precipitation. So, the MIDS result can be multiplied by the runoff ratio to convert it to equivalent terms of the field study. The runoff ratio is derived from the MIDS calculator output that provides the runoff inches from the whole area and the precipitation depth.
5. The UMN calculator gives the infiltration volume of the swale and swale side slope, which is used here to approximate the abstraction volume of the BMP.
6. Rainfall across the swale watershed area should be approximately the same. Therefore, the precipitation volume on a portion of watershed area would be equal to the precipitation volume on the whole watershed multiplied by the portion of the watershed area that is the partial watershed area. Using this relationship, the result of the UMN calculator result can be multiplied by the area portion to convert it to equivalent terms. These values are derived from the land use acreage (shown in Table 2 and Table 3).

The MIDS calculator output includes the abstracted portion of annual rainfall as noted above and also produces a performance goal credit. While the performance goal credit is most relatable to the CSW Permit requirements, converting all the outputs to performance goals was deemed unnecessary for this study. The equivalent terms were deemed sufficient for comparison in this project.

The results from the four methods used to quantify abstraction at the Site 3 and Site 4 study sites are shown in Table 17. These methods show vastly different results, even when transformed to equivalent terms.

Table 17: Four different methods were used to estimate abstraction at the Site 3 and Site 4 swales. The various methods have different result terms which were transformed to equivalent terms. The field study and XP-SWMM terms approximated the equivalent terms, so no transformation was necessary. Upon detailed review of the soils data, Sites 3 and 4 were determined to be HSG D. Both were modeled in XP-SWMM as HSG B infiltration rates. Both the MPCA MIDS and UMN Dry Swale Calculators used HSG B soils for Site 3 and HSG C soils at Site 4.

Method	Calculator Term	Site 3		Site 4	
		Calculator Result (terms vary)	Equivalent Term ($\frac{A_{bmp}}{P_{sw}}$)	Calculator Result (terms vary)	Equivalent Term ($\frac{A_{bmp}}{P_{sw}}$)
Field Study	$\frac{A_{sw}}{P_{sw}}$	HSG D Soils 1% (2018), 53% (2019)		HSG D Soils 13% (2018), -121% (2019)	
SWMM	$\frac{A_{sw}}{P_{sw}}$	HSG B Soils 92% (2018), 86% (2019)		HSG B Soils 95% (2018), 90% (2019)	
MIDS	$\frac{A_{sw+ss}}{RO_{sw}}$	HSG B Soils 36%	13%	HSG C Soils 25%	7%
UMN	$\frac{I_{s+ss}}{P_{pw}}$	HSG B Soils 69%	39%	HSG C Soils 54%	36%

In retrospect, after closer examination of soils data and borings which is discussed in detail in *Design Criteria for Stormwater Volume Reduction Practices* section below, the soils at both Sites 3 and 4 were not HSG B soils due to the presence of clay layers, seasonally-high water tables, and manipulated and compacted soils. Similarly, groundwater could not be addressed in the modeling applications, likely leading to additional overestimation of abstraction.

The most comparable modeling results were from the MIDS and UMN calculator scenarios, because both applications used the same infiltration rates per site (Site 3: HSG B soils and Site 4: HSG C soils). XPSWMM modeling at Site 3 can also be compared to these results because it also used HSG B infiltration rates. At both Sites 3 and 4, the UMN calculator estimated substantially more abstraction (39% and 36%, respectively) than the MIDS calculator (13% and 7%, respectively). XPSWMM modeling estimated substantially more abstraction than the UMN calculator at site 3 (~90% versus 39%). The XPSWMM results are higher than the reference range and appear to illustrate how even sophisticated models can overestimate abstraction if the soils and groundwater are not accurately represented.

The field study results, while reported for comparative purposes, are suspect as previously discussed. Furthermore, later-project soils review work shows that soils at Sites 3 and 4 should have been classified as HSG D soils. Neither the MIDS nor UMN Calculators allow inputs for HSG D soils or the seasonally-high water table (presumably because the CSW Permit does not allow credit for infiltration practices on HSG D soils). Therefore, the same conditions were not used in the models as in the field study, also making comparison of the calculator results to the field results invalid. Given the observed data confidence issues (and the suspected reasons for the issues) as well as the misrepresentation of soils in all model applications (and the inability to correctly represent the soils), the field study results cannot be used to validate either calculator.

Design Criteria for Volume Reduction Practices

The third objective of this study was to assess the study swales against the CSW Permit requirements and additional design recommendations from the MN Stormwater Manual. This objective was added by the report author to explore potential reasons for the low confidence field data, low abstraction ratios and rates shown in the highest confidence data sets, and explore potential issues related to the study swales and relevant to swale design, generally.

Critical design criteria that affect a stormwater management practice's infiltration potential were summarized from the CSW Permit and from the MN Stormwater Manual (SWM) Design Criteria for Infiltration. These criteria represent only a fraction of the design requirements but are key to infiltration potential and effectiveness of the practice as a whole.

1. The bottom of the infiltration practice must be at least three feet above the seasonally saturated soils or bedrock (CSW Permit 16.12 and 16.17).
2. Infiltration areas are not allowed on predominately Hydrologic Soils Group D soils (CSW Permit 16.18).
3. Infiltration areas must be protected from compaction during construction (CSW Permit 16.5).
4. The recommended max contributing area for a dry swale is 5 acres (SWM).
5. Impervious surfaces should constitute greater than 50% of the contributing area to the stormwater practices (SWM).

The study swales were evaluated against these key design criteria to assess whether they would meet these required CSW Permit and other SWM recommended criteria. The first three criteria focus on soils and soils analysis; as such, a detailed soils section is included below. The fourth and fifth criteria addresses contributing area size and composure, which were presented in the Site Selection and Characterization from the report Introduction. Related to criterion 5, additional analysis estimating the ratio of "target runoff" received to all water sources received is presented in the Impervious Surface Runoff Component section below to illustrate the importance of this recommendation.

Soils and Hydrologic Soil Groups

Soils characterization is crucial for the design and functionality of stormwater volume reduction and treatment practices such as roadside swales. Hydrologic Soil Groups (HSGs), commonly used for stormwater practice design and modeling, are soil groupings that describe the runoff potential of soils.

The NRCS National Engineering Handbook (NRCS, 2009) defines HSGs based on four factors: the depth to impermeable layers, depth to the seasonally-high water table, saturated hydraulic conductivity (k_{sat}) of the least transmissive layer in the depth range, and depth to the high water table (Table 18). HSG A soils correspond to low potential runoff (high infiltration), while HSG D soils correspond to high potential runoff (low infiltration). Dual soil classification (e.g. B/D) indicate the drained/undrained HSGs; in other words a B/D soil would function as a D soil unless drainage sufficiently lowers the water table, in which case, it would function as a HSG B soil. Based on the HSG definition, regardless of soil texture, any undrained soil texture with a shallow water table is classified a HSG D soil.

Table 18: Hydrologic Soil Groups (HSGs) are defined based on four criteria (NRCS National Engineering Handbook, Part 630, Chap. 7, 2009).

Depth to water impermeable layer [1/]	Depth to high water table [2/]	K_{sat} of least transmissive layer in depth range	K_{sat} depth range	HSG [3/]
<50 cm [<20 in]	—	—	—	D
50 to 100 cm [20 to 40 in]	<60 cm [<24 in]	>40.0 μm/s (>5.67 in/h)	0 to 60 cm [0 to 24 in]	A/D
		>10.0 to ≤40.0 μm/s (>1.42 to ≤5.67 in/h)	0 to 60 cm [0 to 24 in]	B/D
		>1.0 to ≤10.0 μm/s (>0.14 to ≤1.42 in/h)	0 to 60 cm [0 to 24 in]	C/D
		≤1.0 μm/s (≤0.14 in/h)	0 to 60 cm [0 to 24 in]	D
	≥60 cm [≥24 in]	>40.0 μm/s (>5.67 in/h)	0 to 50 cm [0 to 20 in]	A
		>10.0 to ≤40.0 μm/s (>1.42 to ≤5.67 in/h)	0 to 50 cm [0 to 20 in]	B
		>1.0 to ≤10.0 μm/s (>0.14 to ≤1.42 in/h)	0 to 50 cm [0 to 20 in]	C
		≤1.0 μm/s (≤0.14 in/h)	0 to 50 cm [0 to 20 in]	D
>100 cm [>40 in]	<60 cm [<24 in]	>10.0 μm/s (>1.42 in/h)	0 to 100 cm [0 to 40 in]	A/D
		>4.0 to ≤10.0 μm/s (>0.57 to ≤1.42 in/h)	0 to 100 cm [0 to 40 in]	B/D
		>0.40 to ≤4.0 μm/s (>0.06 to ≤0.57 in/h)	0 to 100 cm [0 to 40 in]	C/D
		≤0.40 μm/s (≤0.06 in/h)	0 to 100 cm [0 to 40 in]	D
	60 to 100 cm [24 to 40 in]	>40.0 μm/s (>5.67 in/h)	0 to 50 cm [0 to 20 in]	A
		>10.0 to ≤40.0 μm/s (>1.42 to ≤5.67 in/h)	0 to 50 cm [0 to 20 in]	B
		>1.0 to ≤10.0 μm/s (>0.14 to ≤1.42 in/h)	0 to 50 cm [0 to 20 in]	C
		≤1.0 μm/s (≤0.14 in/h)	0 to 50 cm [0 to 20 in]	D
	>100 cm [>40 in]	>10.0 μm/s (>1.42 in/h)	0 to 100 cm [0 to 40 in]	A
		>4.0 to ≤ 10.0 μm/s (>0.57 to ≤1.42 in/h)	0 to 100 cm [0 to 40 in]	B
		>0.40 to ≤4.0 μm/s (>0.06 to ≤0.57 in/h)	0 to 100 cm [0 to 40 in]	C
		≤0.40 μm/s (≤0.06 in/h)	0 to 100 cm [0 to 40 in]	D

HSGs are defined by field data, but approximated HSGs are mapped at the landscapes scale via the NRCS Soil Survey (SSURGO). These mapped HSGs are high-level for planning purposes and should not be used for detailed, site-specific planning, particularly when soils have been disturbed through construction or fill. The NRCS National Engineering Handbook (2009) states: "As a result of construction and other disturbances, the soil profile can be altered from its natural state and the listed group assignments generally no longer apply, nor can any supposition based on the natural soil be made that will accurately describe the hydrologic properties of the disturbed soil. In these circumstances, an onsite investigation should be made to determine the hydrologic soil group."

Hydrologic Soil Group definitions do not rely on soil textures, but the NEH identifies the textures typically associated with each HSG when the soils are undisturbed. If disturbed or compacted, soil structure and other related features such as permeability are reduced. Furthermore, the presence of confining layers or groundwater negate these texture associations. The (undisturbed) soil textures typically associated with the HSGs are:

- HSG A: <10% clay and >90% sand or gravel with a gravel or sand texture
- HSG B: 10-20% clay and 50-90% sand with loamy sand or sandy loam textures
- HSG C: 20-40% clay and <50% sand with loam, silt loam, sandy clay loam, clay loam, or silty clay loam textures
- HSG D: >40% clay, <50% sand with clayey textures

Water table and saturated soils are related terms used in the HSG approximation methods in this report. Therefore, these terms are discussed and defined in more detail below.

The water table is the upper surface of the saturated zone in soils. The elevation of the water table varies throughout time, and often reflects seasonal and climatic trends. For instance, the water table tends to be higher in the spring and in wet years, and lower in the fall and in dry years. Surface waters generally reflect the elevation of the water table in the vicinity of the water body. Refer to USGS Circular 1139 for more detailed descriptions.

Seasonally saturated soil is defined by the MPCA CSW Permit as the "highest seasonal elevation in the soil in a reduced chemical state because of soil voids filled with water causing anaerobic conditions. Seasonally saturated soil is evidenced by the presence of redoximorphic features or other information determined by scientifically established methods or empirical field measurements".

Periodically saturated soil is defined in the MPCA Septic Program Rules as the "highest elevation in the soil that is in a reduced chemical state due to soil pores filled or nearly filled with water causing anaerobic conditions. Periodically saturated soil is determined by the presence of redoximorphic features in conjunction with other established indicators as specified in part 7080.1720, subpart 5, items E and F, or determined by other scientifically established technical methods or empirical field measurements acceptable to the permitting authority in consultation with the commissioner".

While the definition of seasonally saturated soils and periodically saturated soils vary slightly, they are largely the same in that assessment of redoximorphic features is required to determine the seasonal or periodic saturated soils depth. The largest difference is that the CSW Permit does not include specific, objective color-based criteria to make this assessment. The SSTS Program criteria are specified in Minnesota Rules, part 7080, and applicable excerpts and definitions are included in Appendix D for reference. Both terms relate to the water table in that the water table would be at or above the saturated soil level seasonally or periodically. As such, the recurring presence of a water table or surface water typically indicate that seasonal or periodic saturated soils are present at that location.

Hydrologic Soil Group Approximation

The HSGs at the swale study sites were approximated using four different methods: 1) desktop review, in particular the NRCS Web Soil Survey, 2) surface MPD measurements, 3) restrictive soil layer analysis, and 4) surface MPD measurements and saturated soils conditions. The original project team used surface MPD measurements and the NRCS Web Soil Survey for initial work on this project. Upon review of water budget results, some unexpected, the report author conducted additional desktop review and reexamined the soil observations to clarify the HSG assessments. The HSG approximation methods and results are described in detail below.

Initial project work did not include sufficient data to fully apply the HSG definitions, which is considered the valid approach to assessing the HSG in this report. However, because different methods to approximate the HSGs were used both in this project and throughout stormwater design field in Minnesota generally, these various methods were applied and reported to provide insight.

Desktop Review

As a preliminary review of each study site, the NRCS Soil Survey Geographic Database (SSURGO) was reviewed for Hydrologic Soil Groups. Other data sources were reviewed for indicators of a shallow water table to indicate the potential presence of saturated soils, including the DNR depth to water table from the MN Hydrogeology Atlas (MHA), the National Wetland Inventory (NWI) wetlands, and Duck's Unlimited restorable wetlands.

Desktop analysis of the SSURGO mapped soils and indicators of a potentially high water table are summarized in Table 19.

Table 19: Desktop review of the SSURGO soils data, MN Geologic Atlas, and other potential indicators of shallow water table indicate that a high water table is likely at sites 1-4 and unlikely at site 5.

Site	SSURGO Mapped Hydrologic Soil Groups	MN Geologic Atlas Depth to Water Table	Other Desktop Water Table Indicators
1&2	Primarily C soils in the immediate study swale watershed B, C, and C/D soils in the upstream watershed	<10 feet through entire area	Several NWI and restorable wetlands found through the area
2	C and C/D soils in the immediate study swale watershed		
3	Primarily C/D soils in the immediate study swale watershed B, C, and C/D soils in the upstream watershed	<10 feet for most of the watershed, with small portions in the 10-20 foot range	Several restorable wetlands have been identified within and near the project area
4	C soils in the immediate study swale watershed C and C/D soils in the upstream watershed	<10 feet deep in the project area and 10-20 feet deep in the upstream watershed	Several NWI wetlands in the surrounding area, but no NWI or restorable wetlands within the project area
5	B soils in the immediate study swale watershed B soils in the upstream watershed	water table is 40 to greater than 50 feet deep	No features in the project area and few wetlands and other water table features in the nearby area

Sites 1-4 show HSG C or C/D soils in the immediate study swale watershed and HSG B, C, and C/D soils in the upstream watershed. These four sites were identified as having groundwater in the less than 10-foot range in the MN Geologic Atlas. Other desktop analyses show existing and restorable wetlands within the vicinity of these project sites. Combined, these factors point to a potentially high water table and HSG D soils. Contrarily, Site 5 appeared unlikely to have a high water table, and SSURGO mapped HSG B soils throughout the area. Maps associated with the review are included in Appendix C.

MPD Infiltrometer and Saturated Hydraulic Conductivity

The saturated hydraulic conductivity (k_{sat}) is a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient – or more simply, the ease with which pores of saturated soil permit water movement. The Modified Phillip Dunn (MPD) infiltrometer is a falling head device developed by the University of Minnesota to measure the saturated hydraulic conductivity of 10-25 cm of soil depth. At each study site, 20-40 MPD measurements were taken at the soil surface. The saturated hydraulic conductivity (k_{sat}) of these measurements was calculated using ASTM D8152. The measurements were grouped by swale feature (i.e. side slope, channel), and the geomean k_{sat} of each feature was calculated (Table 21).

Table 20: The saturated hydraulic conductivity (k_{sat}) was measured at the soil surface at multiple locations per swale feature at each of the sites. The geomean k_{sat} per swale feature is shown here in inches per hour.

Site 1				Site 2			Site 3				Site 4			Site 5			
Side Slope 1	Side Slope 2	Toe slopes & Channel	Channel Center	Side Slope 1	Side Slope 2	Toe slopes & Channel	Side Slope 1	Side Slope 2	Toe slopes & Channel	Channel Center	Side Slope 1	Side Slope 2	Toe slopes & Channel	Side Slope 1	Side Slope 2	Toe slopes & Channel	Channel Center
0.06	0.06	0.06	0.03	0.12	0.17	0.03	0.70	0.86	1.37	4.04	0.16	0.12	0.39	0.68	8.16	0.26	0.58

As a second method to approximate the HSGs of the study sites, the surface k_{sat} values derived from the MPD measurements were applied to the HSG definitions (Table 21). Since the k_{sat} value is just one variable used to determine the HSG, any individual k_{sat} value can corresponded to multiple HSGs, depending on the depth to the high water table and impermeable layers. Since the k_{sat} values were taken at the surface and not at the most restrictive layer in the depth range, applying these k_{sat} values is not technically accurate to assess the HSG, although this was done in this study for comparative purposes.

Table 21: The hydrologic soil group (HSG) classifications derived from the above k_{sat} values vary under different water table and impermeable layer conditions. The depth to high water table and impermeable layers are necessary to assign the HSG.

	Site 1				Site 2			Site 3				Site 4			Site 5			
HSG Assignment Scenairo	Side Slope 1	Side Slope 2	Toe slopes & Channel	Channel Center	Side Slope 1	Side Slope 2	Toe slopes & Channel	Side Slope 1	Side Slope 2	Toe slopes & Channel	Channel Center	Side Slope 1	Side Slope 2	Toe slopes & Channel	Side Slope 1	Side Slope 2	Toe slopes & Channel	Channel Center
No watertable or imp. w/in 40"	D	D	D	D	C	C	D	B	B	B	A	C	C	C	B	A	C	B
Watertable <24", no imp. w/in 40"	D	D	D	D	C/D	C/D	D	B/D	B/D	B/D	A/D	C/D	C/D	C/D	B/D	A/D	C/D	B/D
Impermeable 20-40"	D	D	D	D	D	C	D	C	C	C	B	C	D	C	C	A	C	C
Impermeable within 20"	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D	D

Soil Profile Observations: Restrictive Layers and Saturated Conditions

Soil profile observations were taken in 2016-2017 by MNDOT staff using a hand auger. Six or seven soil profile observations were made across two swale cross-sections per study site, for 12-14 total soil profile observations per study site. The observations were numbered starting at 1) the shoulder of the road, 2) through the inslope of the swale, 3 and 4 (or 3, 4, and 5) at the toe of the slope/bottom of swale, 5 (or 6) up the backslope, and 6 (or 7) at the top of the opposite swale bank, as noted in the Site 1 soil observation notes. The transcribed soil observations for Sites 2-5 did not identify the swale feature or distance from the road, so the author assumed the cross-section observation numbering followed that of Site 1. Soil observations were generally made to a depth of three feet below the surface but were less in several instances due to compaction or obstructions. Soil properties identified in the soil profile

observations included the soil texture, soil matrix and mottling colors using the Munsell soil color system, and compaction.

As a third method to approximate the HSG of the study sites, the least restrictive soil texture was identified from each soil profile observation. This soil texture was referenced along with the typical HSGs per soil textures to estimate the HSG. The identified most restrictive layer per observation are tabulated in Appendix G and discussed by site below. When compaction was noted within three feet of the bottom of the swale channel, the HSG (if not already the most restrictive HSG D soil) was downgraded one HSG per the MN Stormwater Manual guidance regarding compaction. Identification of the most restrictive layer is necessary for accurate application of the HSG criteria. However, cross-referencing the soil texture to determine the HSG is not a technically accurate application to assess HSG, as it does not apply the HSG technical criteria, nor does it consider the effect of loss of soil structure due to disturbance.

Lastly, a fourth method to approximate the HSGs, the soil observation profiles of the study sites were reviewed for the presence of seasonally saturated soils. The soil observations were assessed for signs of seasonal saturation using the periodic saturation soil criteria from MN Subsurface Sewage Treatment Systems (SSTS) Program. Transcribed field soil observations with assessments of topsoil, subsoil, and seasonally saturated soils are in Appendix F. Since any undrained soil texture with a water table within 24 inches is classified as a HSG D soil per the HSG definitions, applying this criterion provided useful assessment for most observations. However, since the MPD measurements were made at the soil surface and not the least transmissive layer, fully applying the HSG definitions using the MPD derived k_{sat} values was not possible where the seasonally saturated soils were not within 24 inches of the surface.

The following soil observation summaries incorporate the third and fourth methods. These summaries were made by the report author, as the staff who originally made the soil observations were no longer working at MNDOT.

Site 1

Twelve soil profile observations were taken at Site 1, six across two swale cross-sections. Observations depths ranged from 6-47 inches (15-120 cm). The parent material is noted as fill, indicating heavy disturbance. The notes indicate that the vegetation included grass and weeds. The soil observations at Site 1 were recorded in centimeters, while the others were recorded in inches. To make the results more comparable, the recorded centimeter values were converted to inches, but are shown in the narrative for ease of review.

The soils textures included clay, silty clay loam, silty loam, loam, and loamy sand. The least transmissive soil texture from individual soil profile observations were silty clay, silty clay loam, and clay for all but two observations. These least transmissive soil textures correlate with low infiltration potential or HSG D soils.

Based on soil and redoximorphic features, nearly every observation at this site shows signs of seasonally saturated soils at 4 inches (10 cm) to 14 inches (36 cm) below the surface. Observations IV, iii, and iv (at the toe of the swale side slope) best represent the swale bottom and showed seasonally saturated soils at 14 inches (36 cm) and 5-6 inches (12-15 cm) below the surface. The depth to the seasonally-high water table results in these soils being categorized as HSG D soils.

Site 2

Twelve soil profile observations were taken at Site 2, six across two swale cross-sections. Observation depths ranged from 34-42 inches, generally. Compaction was noted in nearly all soil profiles, indicating heavy disturbance and likely lower infiltration rates than would be expected based on the soil texture alone. The parent material was not noted but was likely fill, as the site was positioned between two roads. The type of vegetation was not included in the notes.

The observed soil textures included clay, clay loam, loam, sandy clay loam, and loamy sand. The least transmissive soil texture from individual soil observations were clay or clay loam for all but one observation on the road shoulder (where the observation ended at 21 inches deep). These least transmissive soil textures correlate with low infiltration potential or HSG D soils, and when coupled with the observed compaction, these may be considered very low infiltration potential soil profiles.

Based on soil and mottling colors, nearly every observation at this site has seasonally saturated soils at 4-20 inches below the surface. Observations 1-3, 1-4, 3-3, 3-4 (believed to be in the swale bottom) show that the seasonally high water table is 4-8 inches below the surface. The depth to the seasonally-high water table results in these soils being categorized as HSG D soils.

Site 3

Fourteen soil profile observations were taken at Site 3, seven across two swale cross-sections. Observation depths ranged from 19-29 inches, generally. Compaction was noted in most soil profiles, indicating heavy disturbance and likely lower infiltration rates than would be expected based on the soil texture alone. The parent material is not noted, but off-site fill was mentioned once in the notes. Cattails were noted in one observation, and site photos show cattails and willows in the swale – both saturated soil indicators.

The observed soil textures included clay, silty clay, silty clay loam, sandy clay loam, and sandy loam. The least transmissive soil texture from individual soil observations were generally clay or clay loam, particularly in and near the bottom of the swale. These least transmissive soil textures correlate with low infiltration potential or HSG D soils, and when coupled with the observed compaction, these may be considered very low infiltration potential soils.

Based on soil and mottling colors, nearly every observation at this site has seasonally saturated soils at the surface and up to 17 inches below the surface. Observations 1-3, 1-4, 1-5, 3-3, 3-4, 3-5 (believed to be at the swale bottom) show that the seasonally high water table is 0-8 inches below the surface. The depth to the seasonally-high water table results in these soils being categorized as HSG D soils.

Site 4

Thirteen soil profile observations were taken at Site 4, seven across the first cross-section and six across the second cross-section. Observation depths ranged from 19-33 inches. Compaction was noted in two of the soil profiles. The parent material and vegetation were not noted.

The observed soil textures included clay, clay loam, sandy clay loam, silt loam, loam, and sandy loam. The least transmissive soil texture from individual soil profile observations were clay, clay loam, silt clay loam, and sandy clay loam. These textures generally correlate to HSG D soils.

Based on the soil and mottling colors, most of the soil observations indicated seasonally saturated soils at generally 12-22 inches below the surface. However, the observations (believed to be) in the swale bottom showed mixed results: some profiles showed saturated conditions and others showed only faint mottling (without the mottling colors noted). However, some of these observations only extended 24 inches below the surface. The deepest observation 5-4 (believed to be) in the swale bottom was 30-33 inches below the surface and indicated seasonally saturated soils. Deeper observations in the swale

bottom and specifically identified mottling colors would help better identify the HSG of the site overall. While the soil textures are generally more transmissive and saturated soil conditions were less ubiquitous than the first three sites which all showed strong HSG D indicators, the site may overall be functioning at a HSG D soil, albeit with potentially better infiltration than the previous three sites.

Site 5

Fourteen soil profile observations were taken at Site 5, seven at each of two swale cross-sections. Observation depths ranged from 5-27 inches, with six at one foot or less. Compaction, often heavy, was noted at all but one soil profile (hence why the profile depths were shallow). The parent material and vegetation are not noted.

The observed soil textures included silty clay loam, silt loam, loam, sandy loam, loamy sand, and sand. Overall, this site had coarser textured soils compared to the first four sites. The least transmissive soil texture from individual soil profile observations were loam, sandy loam, and sandy clay loam. These textures correlate to HSG B in 5 profiles and HSG D in 8 profiles. When considering the compaction in tandem with the texture, these soil profiles may function as a HSG C or D.

Only two of the individual soil profile observations showed signs of seasonally saturated soils. However, the observations generally were not sufficiently deep to adequately assess for confining layers (need 40”) or seasonally high water table (24” for HSG definition and 36” to meet permit requirements).

Impervious Surface Runoff Component

Swales receive water from multiple sources including direct precipitation, runoff from local pervious areas, runoff from local impervious areas, and flow from an upstream channel. The target runoff in this context is considered the runoff from the new impervious surface area. The target runoff is an important consideration because it is the basis for the CSW Permit. In other words, the CSW Permit aims to mitigate the volume and pollutants created by new impervious surfaces. While the study swales did not inlcude a “new” impervious area component, runoff from the road within the immediate study swale watershed is somewhat analagous or can be inferred to be the target runoff.

When the treatment capacity of a practice is exceeded, not all of the target runoff will be treated. To prevent a practice from being overwhelemed by non-target runoff and hence minimally treating target runoff, design guidance specifies that a maximum contributing area and minimum ratio of impervious surface (criteria 4 and 5). The proportions of the different sources can also be used to approximate the portion of the source water that is treated if the total treatment volume is known.

For this study, the proportions of water received from the various sources were approximated by multiplying the contributing area of each source by an estimated runoff ratio and dividing by the sum of these values. For areas upstream of the study watershed, the runoff ratios from the MN Stormwater Manual (McCuen, 2017) were used with an additional reduction of 0.2 to account for additional abstraction that may occur in the upstream swale. The effective runoff ratio used for direct precipition on the immediate study swale watershed is 100%, including the road. Using 100% for the immediate swale watershed and the additional 0.2 reduction in upstream runoff ratio provides a higher estimate of the total local impervious surface runoff component and hence can be a considered liberal estimate.

At Site 3 and Site 4, approximately 13% and 15% (respectively) of the water (direct precipitation and runoff) that the swale receives is from the road within the swale watershed. The analysis is included in Appendix E. This analysis illustrates how the target runoff (i.e. runoff from the new impervious area) to a swale may only constitute a small fraction of the total water received by the swale. Once the abstraction

capacity of the swale area is exceeded, water from all sources will be conveyed downstream with minimal treatment.

Design Criteria Summary and Discussion

Table 22 shows the critical design criteria and assessment of the study swales against these criteria. The first three criteria are requirements from the CSW Permit, and the last three are recommendations from the MN Stormwater Manual.

Table 22: The study swales were compared against five critical design criteria. Overall, the study swales did not meet several of these criteria.

Critical Design Criteria	Assessment of Swales Against Criteria
The bottom of the infiltration practice must be at least three feet above the seasonally saturated soils or bedrock (CSW Permit 16.12 and 16.17).	The soil observations at Sites 1-4 show seasonally saturated soils within three feet of the bottom of the swale. These sites would not meet the CSW Permit requirement.
Infiltration areas are not allowed on predominately Hydrologic Soils Group D soils (CSW Permit 16.18).	The soil observations at Sites 1-4 show HSG D soils due to shallow water table in addition to low permeability soils within the depth range. Sites 1-4 do not meet the CSW Permit requirement. The fifth site could not be assessed for a HSG because the full set of criteria to classify the HSG was not made.
Infiltration areas must be protected from compaction during construction (CSW Permit 16.5).	The soil observations at every site show compaction, particularly at Site 5. This indicates that the sites were not protected during construction, which does not meet the CSW Permit requirement. Furthermore, if compaction limits infiltration, the compaction could be considered a confining layer and be classified as HSG D soils.
The recommended max contributing area for a dry swale is 5 acres (SWM).	Sites 1 and 3 had watersheds in excess of 5 acres. Since the total infiltration potential of any infiltration area is relatively fixed, large upstream watersheds effectively reduce the infiltration potential of an infiltration area.
Impervious surfaces should constitute greater than 50% of the contributing area to the stormwater practices (SWM).	Impervious surface constituted 25% of the total Site 3 area and 14% of the total Site 4 area. The data were not reviewed in detail for the remaining sites, but based on aerial imagery, they also appear to be roughly in the 20% range.

In earlier work on this project, the infiltration potential of soils at the study sites was generally overestimated because only surface MPD measurements were used to classify the HSG. Based on closer review and analysis of the soil observations and application of the HSG definition, Sites 1-4 are classified as HSG D soils. This result along with unrelated stormwater project review work (not addressed in this report) show that soil HSG classification would be improved by a more detailed application of the HSG definition, in particular, assessment of the restrictive layer k_{sat} and the depth to seasonally saturated soils and impermeable layers.

Additional evidence of low infiltrating soils can be seen in the vegetation at the study sites. In particular, Site 3 (shown on cover) is dominated by cattails and willows, both wetland indicators. Furthermore, observed in desktop analysis, wetland and restorable wetlands are common features in the project areas, and the water table is documented as shallow (less than 10 feet from the soil surface) by the DNR. These limited results suggest that desktop analysis for wetland features may be useful for indicating potential HSG D soils.

Based on the soil profiles, gravelly soils on the road shoulder are common, where infiltration of a limited water volume and time may readily occur. Similarly, surface soils throughout the swale contain macropores, root channels, and other features that make the surface soils more transmissive. However, the surface soils do not reflect soils within the depth range (40 inches) necessary to assess the HSG. When soils within the depth range restrict permeability, the overall effect is to limit the infiltration potential of the swale. Figure 29 (in contrast to Figure 1 at the beginning of this report) shows one potential effect of HSG D soils: water can infiltrate into the transmissive side slopes but then discharge into the channel due to restrictions deeper in the soil profile. Once the pore space within the surface soils is filled, water will simply runoff into the swale channel and continue downstream with minimal treatment.

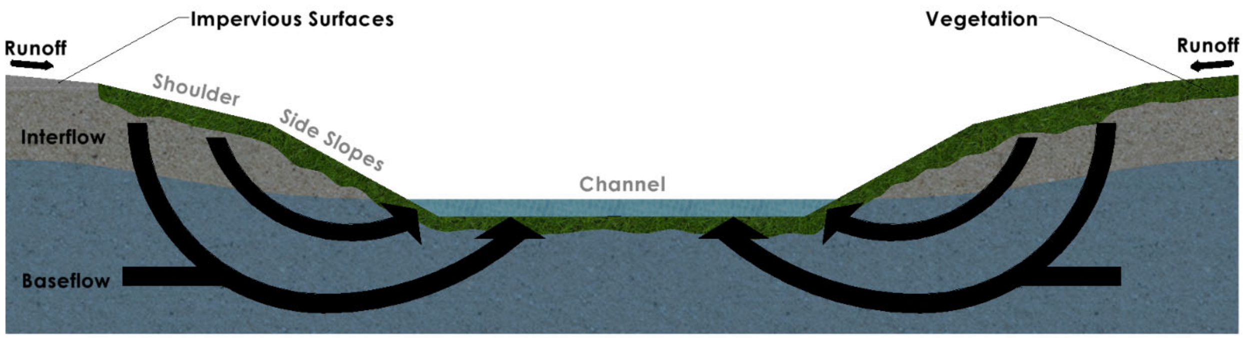


Figure 29: HSG D soils with most restrictive layers deeper in the soil profile can lead to the swale channel intercepting runoff that infiltrated in the higher elevation, more porous surface soils of the swale side slope.

The HSG D soils and high water table were not the only issues affecting the infiltration potential of the study swales. A comparison of the study sites to the CSW Permit requirements and MN Stormwater Manual recommendations for infiltration areas showed that sites 1-4 would not most criteria, and Site 5 would not meet at least one criterion. In summary, the identified infiltration-limiting criteria included high-water table, clayey soils, compacted soils (i.e. areas were not protected during construction), and excessive contributing drainage areas.

The contributing drainage area may be an underemphasized criterion with the potential to substantially affect an infiltration area's ability to address the target runoff (target runoff being one inch from the new impervious area). For sites 3 and 4, runoff from the road within the study watershed to the study swale was estimated to be 13% and 15% of the total water received by the swale. Effectively, much of the target runoff was not treated in the swale due to the total amount of runoff overwhelming the swale's infiltration potential. More robust modeling could be done to better quantify the portion of the target runoff that is infiltrated, but areas with large contributing areas to small treatment footprints will inherently be unable to adequately address the target runoff.

Conclusions

The objectives of this study were to: 1) quantify the volume removal (referred to as abstraction, which includes infiltration, evapotranspiration, and storage) occurring in road-side swales using a simplified water budget and 2) model abstraction at the field sites using three models and compare the model and field study results. A later goal developed by the report author was to 3) assess the study swales against critical design requirements and recommendations to illuminate potential causes for low confidence data and low abstraction rates and ratios.

Objective 1: Quantify Swale Abstraction

Five swale sites were studied over a multi-year period by isolating a section of the swale using an upstream and downstream weir, measuring water level and precipitation, and applying analysis methods including a simplified water budget application. The simplified water budget, which assumed ground water was negligible, allowed for runoff and abstraction (combined infiltration, evapotranspiration, and storage) to be deduced from the water level and precipitation data.

Nine site-year seasonal data sets were collected and analyzed to develop runoff and abstraction ratios on a seasonal and rainfall-runoff event basis. Generally, confidence in the accuracy of the data was low. The seasonal runoff ratios varied from -527% to 233%, four of the nine were outside of the feasible range of 0-100%. The two data sets with the highest estimated confidence showed 99% and 87% seasonal runoff ratios, corresponding 1% and 13% seasonal abstraction ratios. The rainfall-runoff event-based runoff ratios for all sites ranged from -1,023% to 1,962%. The rainfall-runoff abstraction rates for the highest estimated confidence data sets were between -0.02 to 0.06 inch per hour, analyzed at the event time scale.

The data or assumptions associated with the water budget analysis generally appear problematic, therefore abstraction could not be estimated with reasonable confidence. Based on characteristics of the data and reports from the original project team, issues with this in-field water budget application may include:

- Groundwater discharge
- Seepage around weirs
- Backwater effect
- Instrumentation errors/drifting
- Inaccurate watershed size estimate
- Complicated flow dynamics
- Data correction and analysis
- Subbing precipitation from offsite locations

The largest suspected issues based on the characteristics of the data are groundwater discharge, seepage around the weirs, and inaccurate watershed size estimates. The high water table was likely contributing groundwater discharge to many of the sites, invalidating the assumptions of the simple water budget used in this analysis. Due to these issues and despite a high amount of rigor by the original project team, quantifying abstraction in roadside swales - with confidence - was not successful in this project.

Objective 2: Model Abstraction and Comparison to Field Results

Three models, the MPCA MIDS calculator, the UMN Dry Swale Calculator, and XPSWMM were used to model the Site 3 and 4 study swales because these two sites each had a site-year data set with the highest confidence. Model results were transformed to (as close as possible) equivalent terms, and the results compared to the field results.

Modeled and transformed abstraction ratio estimates ranged from 92% to 13% at Site 3 and from 95% to 7% at Site 4. However, comparison amongst the various model outputs and comparison of these to

the field data should be done cautiously because: 1) the field data were suspect and may not be useful for comparisons, 2) neither the MPCA nor UMN tool accommodate HSG D soils (and Sites 1-4 were later found to have HSG D soils), 3) XPSWMM modeling assumed HSG B infiltration rate soils and did not account for high groundwater, and 4) while the outputs were transformed to equivalent units, assumptions were necessary to make these transformations and the results may not be categorically comparable.

Model comparison was further complicated because each tool gives a different result term, but the result terms were transformed into (as close as possible) equivalent terms (Table 23). One result of the modeling exercise was to illustrate how more robust modeling efforts can be undermined by incorrect inputs. For example, the XPSWMM modeling efforts did not use accurate soils data, other inputs were unclear, and the resulting runoff ratio was well above the reference range and any other estimate produced in this study.

Table 23: The transformed (to equivalent terms) abstraction ratio estimates vary substantially.

Method	Site 3	Site 4
Field Study	1%, 53%	13%, -121%
XP-SWMM	92%, 86%	95%, 90%
MIDS	13%	7%
UMN	39%	36%

Of key interest, the MIDS calculator results and the UMN calculator results were compared after transforming the calculator outputs to equivalent terms. While the sites could not be modeled as HSG D soils due to limitations in both of the calculators, both sites 3 and 4 were modeled using the same soil infiltration rates in both of the calculators. In this way, the results were comparable. At both sites 3 and 4, the UMN calculator estimated substantially more abstraction (39% and 36%, respectively) than the MIDS calculator (13% and 7%, respectively). Comparing these results to the field study results, the MIDS calculator better aligned with the field results, but again, the field results were suspect, and the models could not accurately represent the onsite soils.

A review of the model inputs shows that the MIDS calculator includes more considerations. Of particular concern, the UMN calculator does not consider the effect of the upstream contributing area or the actual dimensions of the swale. A detailed review of the methods and robustness of these calculators was beyond the scope of this study, however.

Objective 3: Assess Study Swales for Conformity to Design Criteria

Since quantification of swale abstraction (objective 1) did not yield high confidence results, soils data was reviewed in detail to shed light on suspected issues with the project, which evolved into objective 3. Five critical design criteria were reviewed, three of which are related to soils and required by the CSW Permit.

Soils review incorporated desktop analysis, soil observations, and MPD measurements. Sites 1-4 were mapped in the NRCS SSURGO database as generally HSG C soils. However, surface water table features were observed near these same study sites in desktop imagery reviews. Field soil observations revealed a range of soil types, disturbed soils, and saturated soil conditions, resulting in Sites 1-4 being classified as HSG D soils. This limited review suggests that areas near observable water table or wetland type features (and without large changes in elevation or other extenuating circumstances) should be field-investigated as likely HSG D soils, regardless of the SSURGO database results. Likewise, areas that were likely impacted during historical construction will likely have compacted conditions, which could result in

impermeable soil layers and a HSG D classification. Desktop analysis of soils and the water table can provide high level planning information but must be used with caution and verified by field observations.

Soils at the study sites was originally estimated as more transmissive than later assessed because only surface k_{sat} measurements were initially used to classify the soils. The definition of HSGs was later applied, which uses the depth to the high water table, depth to impermeable layers, and the k_{sat} of the least transmissive layer within the depth range. k_{sat} measurements of the least transmissive layer in the depth range were not obtained. However, based on the high water table (assessed as periodically/seasonally saturated soils), Sites 1-4 were classified as HSG D soils (or dual soil groups). If the high water table were not encountered at Sites 1-4, the HSG could not be determined from the surface k_{sat} values, as was the case for Site 5. The more transmissive surface k_{sat} values were likely reflect the macropores, root channels, and other more transmissive conditions than underlying subsoils and particularly, the least transmissive layer.

Overall, Sites 1-4 did not meet several of the identified critical design criteria. A key take-away being that accurate characterization of soil in (proposed) infiltration areas is critical from both the experimental perspective of this project, specifically, and in the effectiveness of infiltration projects, generally. The soil types, structure (condition/disturbance), and high water table likely hindered infiltration at these sites. Other critical design criteria, the contributing area and ratio of pervious and impervious area, were also exceeded at some of the project sites. Infiltration areas that are inundated by runoff from excessive contributing areas will inherently have limited capacity to treat the target runoff. As such, these criteria may warrant a closer review when designing infiltration practices for water quality treatment and volume reduction goals.

Appendix

Appendix A: Detailed Weir Set-up Description

Weirs were constructed from 4’ x 8’ x 0.0875” aluminum sheets. A 20” deep right triangle was cut in the top-center of the long side of an aluminum sheet by staff at a MnDOT sign shop (Oakdale, MN). The dimensions of all weir cuts were verified with rulers and carpenter squares. The edges of weir cuts were smoothed and beveled with machinist’s files and/or an angle grinder as needed.

Where weirs were placed in open swale channels, a 12”-wide trench was excavated with a backhoe across the channel to a depth of roughly 2’ below center channel grade. The 4’ x 8’ weir plate was installed level and plumb across the channel so that the weir notch was situated approximately 4” above-grade at the center of the weir channel. The weir plate was secured to adjacent vertical traffic safety-compliant 4” x 4” x 10’ wood posts with galvanized metal bolts. When the edges of the weir plate did not extend fully (i.e., to the top edge of the weir plate) into either swale side slope, the weir plate was extended by bolting an additional 4’ x 8’ metal sheet to the edges of the center weir plate. The weir was then relevelled with the backhoe, and native soil was backfilled and compacted to the weir plate bottom level. All plate joints were sealed with White Lightning Storm Blaster elastomeric sealant rated for submerged outdoor applications (White Lightning, Cleveland, OH). Weirs were completed by packing bentonite along the upstream faces of weir plate joints and the bottom edges of weir plates, backfilling with native soils, and then machine and manual compaction of soils to match pre-installation contours at ground level. To prevent encroachment of vegetation, detritus, and debris on the weir, a rock layer rock (1-2”) was then spread across the weir pool for a distance of roughly eight feet upstream of the notch. For the same purpose, yellow safety fencing (2” mesh) was secured around the edges of the weir pool. For safety and visibility, yellow reflective pavement marking tape was applied to the horizontal upper edges of weir plates. As a traffic safety measure at S3-S4, rock (1-2”) berms were developed from the side slope surface to the top outside edges of weir plates. These berms were installed such that they did not violate the necessary weir pool configuration for flow monitoring. Weir configuration and finishing was completed in accordance with standard recommendations for partially-contracted, 90-degree v-notch weirs.

Three S5 weirs were installed in concrete stormwater conveyances. Two of these were installed in pre-cast manhole structures at the outlet pipe joint. Here, the 4’ x 8’ weir plate was cut to a size to fit flush across the flat upstream end of the outlet pipe. The weir plate was affixed to the end of the outlet pipe with elastomeric sealant and reinforced with 2x4s leveraged against the upstream fact of the weir plate and the opposite side of the manhole structure. The side and bottom edges of both the upstream and downstream weir faces were again sealed with elastomeric sealant, and allowed to dry as there was no precipitation for at least 48h after installation. Finally, one weir was installed within an elliptical conveyance pipe near the outfall apron. This weir was cut to match the shape of the pipe, and installed and secured primarily in the pipe by static friction. Elastomeric sealant was applied along the entire intersection of pipe and weir plate and allowed to dry for 2 days. Heavy rocks (~10”) were placed on the downstream weir face as reinforcement.

After installation and into the early stages of field monitoring, all weirs were observed for signs of potential leakage. When any potential leakage was noted, weirs were resealed with digging, application of bentonite and/or elastomeric sealant, and/or re-compaction as applicable and necessary.

For monitoring head at the weir, the Ott Orpheus Mini sensors were installed in stilling wells fabricated from 4” diameter PVC pipe. Stilling well boreholes were hand- or machine-augured to a depth of approximately 18”. The stilling wells were then placed plumb into the boreholes, which were then backfilled with native soils and a bentonite seal and compacted with manual tools. A water level sensor was then suspended in each stilling well with its position marked and recorded in field notes, photographs, and later with survey measurements. Water level sensors were programmed to record water level, temperature, and battery level at two-minute increments. The bottom of the sensors’ metal housing (not the attached rubber foot) was used as the program reference point. Sensor lengths were measured and water level readings were calibrated prior to installation and between monitoring years using five-gallon buckets. This was of critical importance as sensor lengths often deviated by ≥1cm from the manufacturer’s specifications, and the position of the pressure transducer was ~5mm above the bottom of the metal housing. Following measurement, these observations were confirmed by the manufacturer’s technical support staff; this information was not readily apparent in the product manual. Sensor length was ultimately measured under the influence of gravity (i.e., sensors were hung vertically for measurement), as it was recognized that the sensor cables retained curvature from their packaging and shipping, which the weight of the probe and cable did not overcome when hung vertically, thereby shortening the effective length of some sensors. Again, it was critical to gain precise data on effective sensor length and response calibration, as small deviations (3-5 mm) can introduce error into flow calculations, and these would not have been noticed if they had not been checked against manufacturer specifications.   - David Fairbairn, (former) MPCA Stormwater Research Scientist

Some specific issues with the field set-up and potential data collection identified through interview with the original project team include:

- Water nearly continuously present in some swales (which indicates high groundwater or groundwater discharge and also could result in higher evaporation)
- Difficulty estimating watershed areas (which impacts the precipitation volume measurement and resulting calculations)
- Equipment malfunctions
- Holes drilled in the weir to drain water (Site 3, 2018)
- Potential water overtopping of weirs (which would substantially skew the flowrate of high flows)

Appendix B: MIDS Calculator Inputs and Outputs

Site 3 MIDS Scenarios

	Scenario 1: Roadside of Study Swale Immediate Watershed (road & shoulder/swale side slope using side slope BMP only)	Scenario 2: Roadside and grassside of Study Swale Immediate Watershed (scenario 1 adding in grass side slope, using side slope BMP only)	Scenario 3: Immediate Study Swale Area including swale (same as 2 but then route swale side slopes to swale channel)	Scenario 4: Study Swale Full Watershed (Scenario 3 and adding in upstream acres).
Zip Code	55318			
(Annual Rainfall in)	29.7			
Retention Requirement (in.)	1			
Area Land Cover				
Impervious (acres)	0.216	0.216	same as previous scenario	0.876
Magaged Turf (acres) - Use B soils at Site 3	0.372	0.877		2.561
Sum	0.588	1.093		3.437
Swale Side Slope BMP (road side)				
Acres and soil type/impervious	.372 B, .216 Imp	same as previous scenario	same as previous scenario	same as previous scenario
H:V	(6:1)			
Flow Path Length	29			
Channel Length	680			
HSG	B, 0.45 in/hr			
Vegetation (for Manning's N)	Mowed Turf			
Swale Side Slope BMP (grass side)				
Acres and soil type/impervious	n/a	0.505 B	same as previous scenario	same as previous scenario
H:V		(3:1)		
Flow Path Length		38		
Channel Length		680		
HSG		B, 0.45 in/hr		
Vegetation (for Manning's N)		Mowed Turf		
Swale Main Channel BMP				
acres (above what is routed via side slope areas)	n/a	n/a	0	1.684 B, 0.66 Imp
Channel Length (ft)			680	same as previous scenario
Swale bottom width (ft)			11	
Slope			1.75%	
HSG			B, 0.45 in/hr	
Vegetation (for Manning's N)			Mowed Turf	
Results				
Performance Volume Goal (ft^3)	784	784	784	3180
Performance Volume Goal (ac-in)	0.216	0.216	0.216	0.876
Performance Goal (inches from imp acres)	1	1	1	1
Volume Removed by BMPs toward perf. goal (ft^3)	20	20	439	556
Volume Removed by BMPs (inches from imp acres)	0.03	0.03	0.56	0.17
Performance Goal Retained (event based)	3%	3%	56%	17%
Annual Runoff Volume (ac-ft) (Post Development)	0.6228	0.8478	0.8478	2.9947
Annual Runoff Volume (ft^3)	27,129	36,930	36,930	130,449
Annual Runoff (in. from all area)	12.7	9.3	9.3	10.5
Annual Runoff Volume Removed by BMPs (ac-ft)	0.0717	0.1095	0.517	1.0675
Annual Runoff Volume Removed by BMPs (ft^3)	3,123	4,770	22,521	46,500
Annual Runoff Volume Removed by BMPs (in.)	1.5	1.2	5.7	3.7
Removed Portion of Annual Runoff (annual based)	10%	13%	61%	36%

Site 3, Scenario 3 details

BMP Summary

Performance Goal Summary

BMP Name	BMP Volume Capacity (ft3)	Volume Recieved (ft3)	Volume Retained (ft3)	Volume Outflow (ft3)	Percent Retained (%)
1 - Swale Side Slope	20	784	20	764	3
0 - Swale Side Slope	106	0	0	0	0
1 - Swale main channel	419	764	419	345	55

Annual Volume Summary

BMP Name	Volume From Direct Watershed (acre-ft)	Volume From Upstream BMPs (acre-ft)	Volume Retained (acre-ft)	Volume outflow (acre-ft)	Percent Retained (%)
1 - Swale Side Slope	0.6228	0	0.0717	0.5511	12
0 - Swale Side Slope	0.225	0	0.0378	0.1872	17
1 - Swale main channel	0	0.7383	0.4522	0.2861	61

Site 3, Scenario 4 details

BMP Summary

Performance Goal Summary

BMP Name	BMP Volume Capacity (ft3)	Volume Recieved (ft3)	Volume Retained (ft3)	Volume Outflow (ft3)	Percent Retained (%)
1 - Swale Side Slope	20	784	20	764	3
0 - Swale Side Slope	106	0	0	0	0
1 - Swale main channel	536	3160	536	2624	17

Annual Volume Summary

BMP Name	Volume From Direct Watershed (acre-ft)	Volume From Upstream BMPs (acre-ft)	Volume Retained (acre-ft)	Volume outflow (acre-ft)	Percent Retained (%)
1 - Swale Side Slope	0.6228	0	0.0717	0.5511	12
0 - Swale Side Slope	0.225	0	0.0378	0.1872	17
1 - Swale main channel	2.1469	0.7383	0.958	1.9272	33

Site 4 MIDS Scenarios

	Scenario 1: Roadside of Study Swale Immediate Watershed (road & shoulder/swale side slope using side slope BMP only)	Scenario 2: Roadside and grassside of Study Swale Immediate Watershed (scenario 1 adding in grass side slope, using side slope BMP only)	Scenario 3: Immediate Study Swale Area including swale (same as 2 but then route swale side slopes to swale channel)	Scenario 4: Study Swale Full Watershed (Scenario 3 and adding in upstream acres).
Zip Code	55012			
(Annual Rainfall in)	30.6			
Retention Requirement (in.)	1			
Total Area Land Cover				
Impervious (acres)	0.306	0.306	same as previous scenario	0.625
Magaged Turf (acres) - Use C soils for site 4	0.523	0.826		3.734
Summed	0.829	1.132		4.359
Swale Side Slope BMP (road side)				
Acres and soil type/impervious	.523 C, .306 Imp	same as previous scenario	same as previous scenario	same as previous scenario
H:V	(3:1)			
Flow Path Length	17			
Channel Length	800			
HSG	C, 0.2 in/hr			
Vegetation (for Manning's N)	Mowed Turf			
Swale Side Slope BMP (grass side)				
Acres and soil type/impervious	n/a	0.303 C Soils	same as previous scenario	same as previous scenario
H:V		(4:1)		
Flow Path Length		11		
Channel Length		800		
HSG		C, .2 in/hr		
Vegetation (for Manning's N)		Mowed Turf		
Swale Main Channel BMP				
acres (above what is routed via side slope areas)	n/a	n/a	0	2.908 C, .319 Imp
Channel Length (ft)			800	same as previous scenario
Swale bottom width (ft)			10	
Slope			1.30%	
HSG			C, 0.2 in/hr	
Vegetation (for Manning's N)			Mowed Turf	
Results				
Performance Volume Goal (ft^3)	1111	1111	1111	2269
Performance Volume Goal (ac-in)	0.306	0.306	0.306	0.625
Performance Goal (inches from imp acres)	1	1	1	1
Volume Removed by BMPs toward perf. goal (ft^3)	1	1	356	460
Volume Removed by BMPs (inches from imp acres)	0.0009	0.0009	0.32	0.20
Performance Goal Retained (event based)	0%	0%	32%	20%
Annual Runoff Volume (ac-ft) (Post Development)	0.9312	1.0842	1.0842	3.248
Annual Runoff Volume (ft^3)	40,563	47,228	47,228	141,483
Annual Runoff (inches from summed area)	13.5	11.5	11.5	8.9
Annual Runoff Volume Removed by BMPs (ac-ft)	0.0043	0.0077	0.4505	0.8112
Annual Runoff Volume Removed by BMPs (ft^3)	187	335	19,624	35,336
Annual Runoff Volume Removed by BMPs (in.)	0.06	0.08	4.8	2.2
Removed Portion of Annual Runoff (annual based)	0%	1%	42%	25%

Site 4, Scenario 3 details

BMP Summary

Performance Goal Summary

BMP Name	BMP Volume Capacity (ft3)	Volume Recieved (ft3)	Volume Retained (ft3)	Volume Outflow (ft3)	Percent Retained (%)
1 - Swale Side Slope	1	1111	1	1109	0
2 - Swale Side Slope	8	0	0	0	0
0 - Swale main channel	355	1109	355	755	32

Annual Volume Summary

BMP Name	Volume From Direct Watershed (acre-ft)	Volume From Upstream BMPs (acre-ft)	Volume Retained (acre-ft)	Volume outflow (acre-ft)	Percent Retained (%)
1 - Swale Side Slope	0.9312	0	0.0043	0.9269	0
2 - Swale Side Slope	0.153	0	0.0034	0.1496	2
0 - Swale main channel	0	1.0765	0.4428	0.6337	41

Site 4, Scenario 4 details

BMP Summary

Performance Goal Summary

BMP Name	BMP Volume Capacity (ft3)	Volume Recieved (ft3)	Volume Retained (ft3)	Volume Outflow (ft3)	Percent Retained (%)
1 - Swale Side Slope	1	1111	1	1109	0
2 - Swale Side Slope	8	0	0	0	0
0 - Swale main channel	459	2267	459	1809	20

Annual Volume Summary

BMP Name	Volume From Direct Watershed (acre-ft)	Volume From Upstream BMPs (acre-ft)	Volume Retained (acre-ft)	Volume outflow (acre-ft)	Percent Retained (%)
1 - Swale Side Slope	0.9312	0	0.0043	0.9269	0
2 - Swale Side Slope	0.153	0	0.0034	0.1496	2
0 - Swale main channel	2.1637	1.0765	0.8035	2.4367	25

Appendix C: Mapped SSURGO HSGs and Water Table Indicators

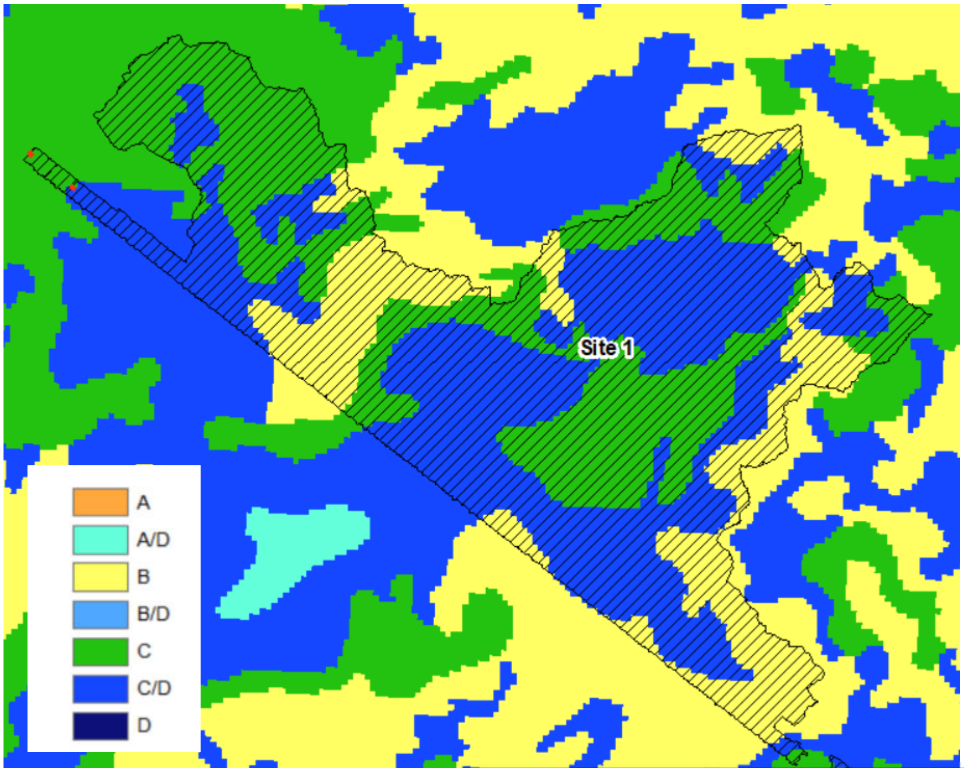


Figure 30: As mapped in the SSURGO soils database, the watershed upstream of the Site 1 study swale contains B, C, and C/D soils, and the immediate study swale watershed is primarily C soils.

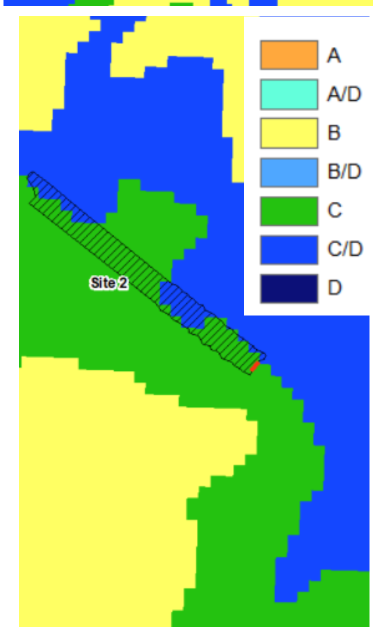


Figure 31: As mapped in the SSURGO soils database, the Site 2 study swale (which has no additional upstream watershed) contains C and C/D soils.

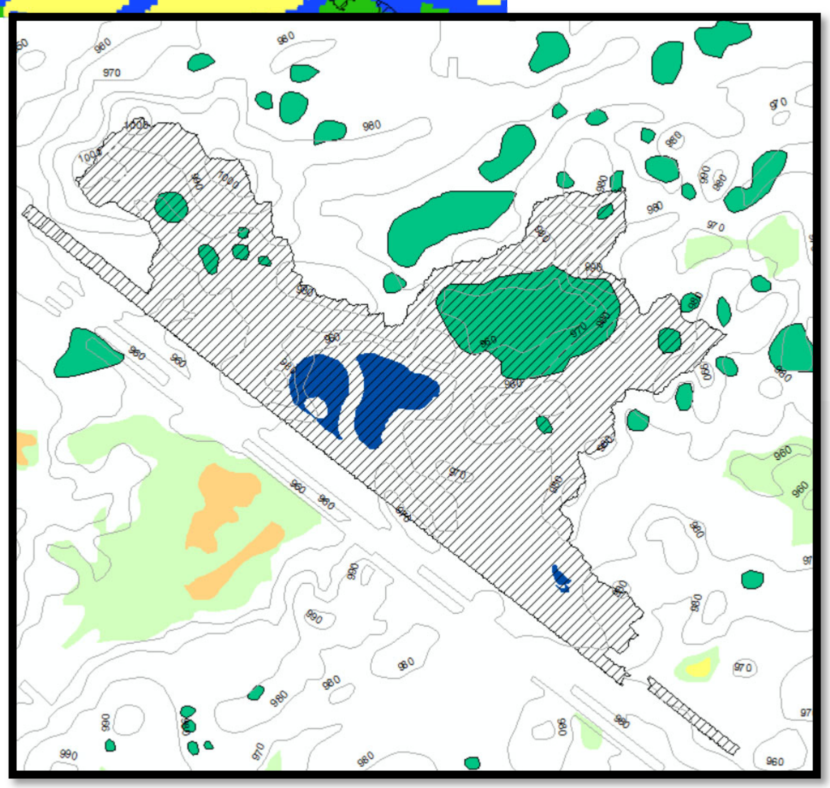


Figure 32: At Sites 1 and 2, the MGA indicates that the depth to the water table is less than 10 feet throughout the watershed area. Several NWI and restorable wetlands area found within the project area.

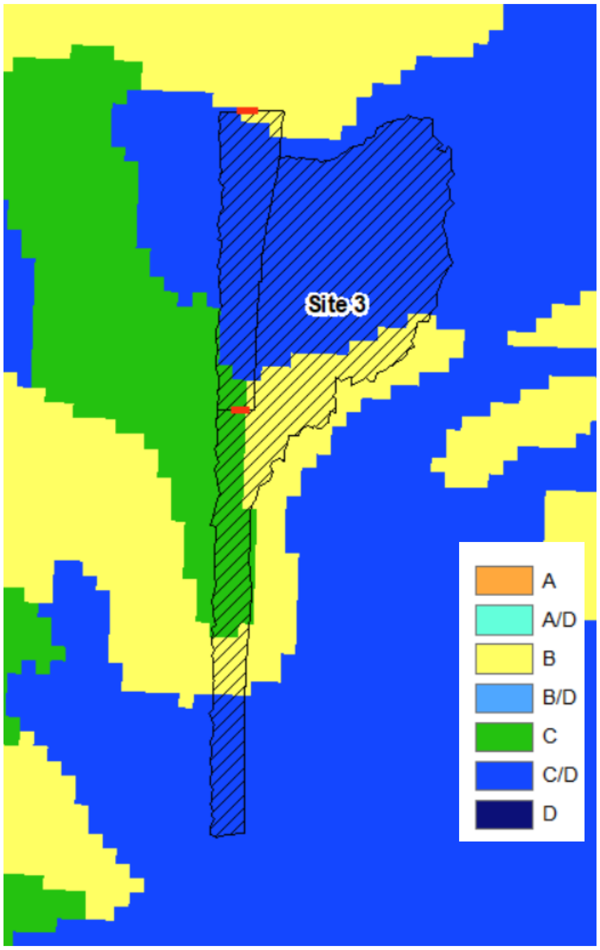


Figure 34: As mapped in the SSURGO soils database, the watershed upstream of the Site 3 study swale contains B, C, and C/D soils, and the immediate study swale watershed is primarily C/D soils.

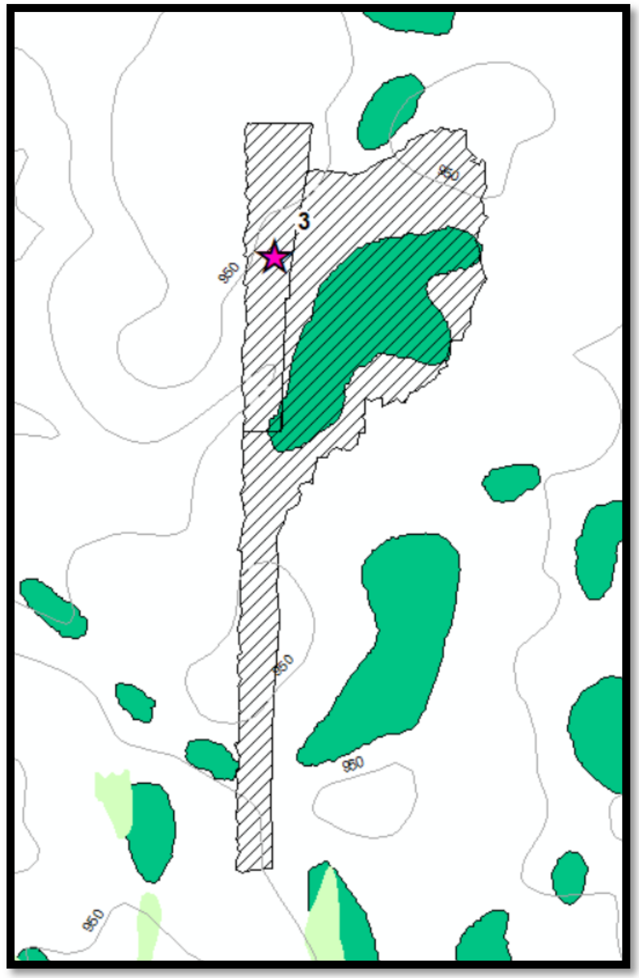


Figure 33: At Site 3, the MGA indicates that the majority of the watershed area is less than 10 feet to the water table with small portions in the 10-20 foot range. Several restorable wetlands have been identified within and near the project area.

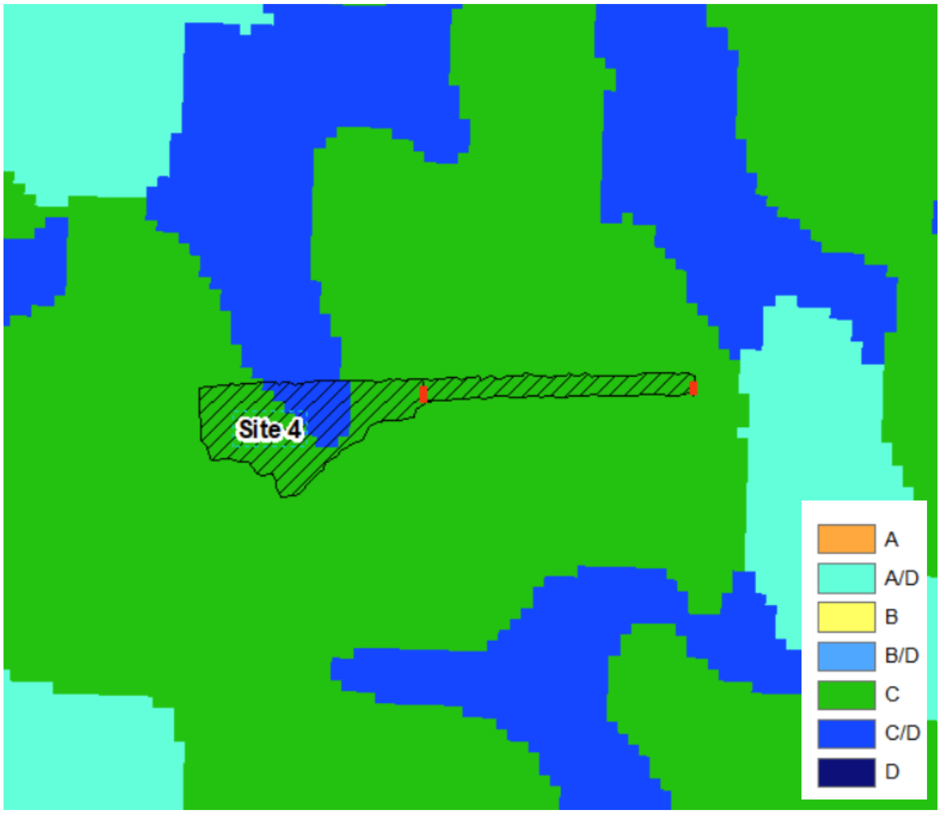


Figure 36: As mapped in the SSURGO soils database, the watershed upstream of the Site 4 study swale contains C, and C/D soils, and the immediate study swale watershed is C soils.

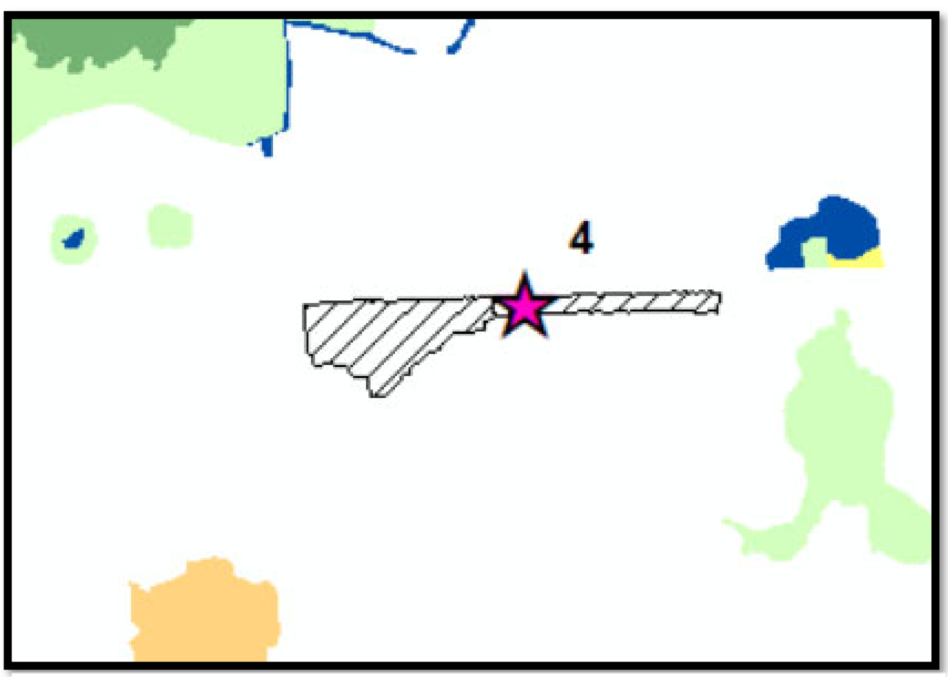


Figure 35: At Site 4, the MGA indicates that the water table is less than 10 feet deep in the project area and 10-20 feet deep in the upstream watershed. While several NWI wetlands are in the surrounding area, no NWI or restorable wetlands were identified within the project area.

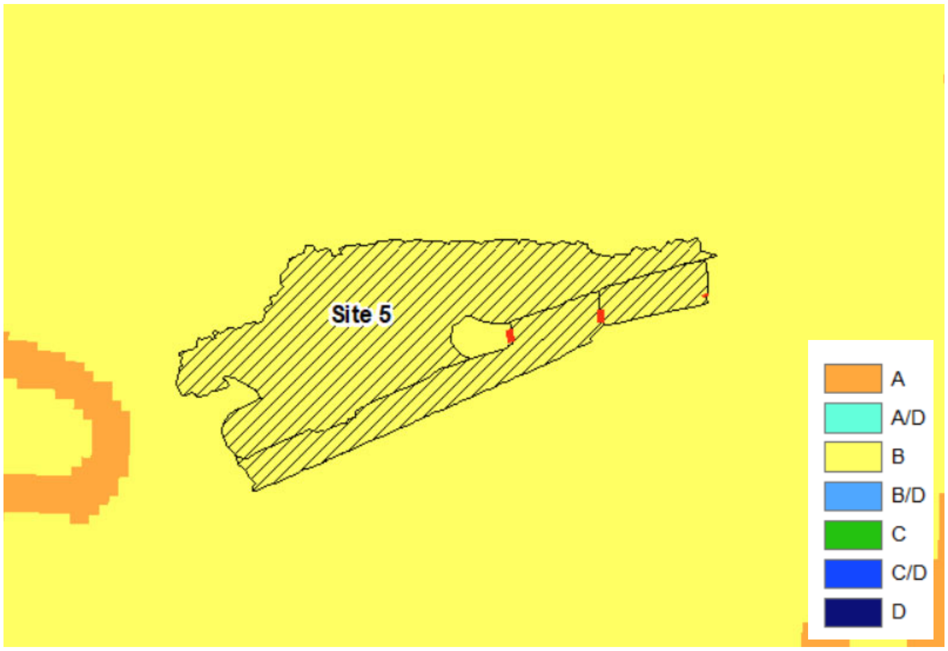


Figure 37: As mapped in the SSURGO soils database, the watershed upstream of the Site 5 study swale and the study swale both contain B soils.

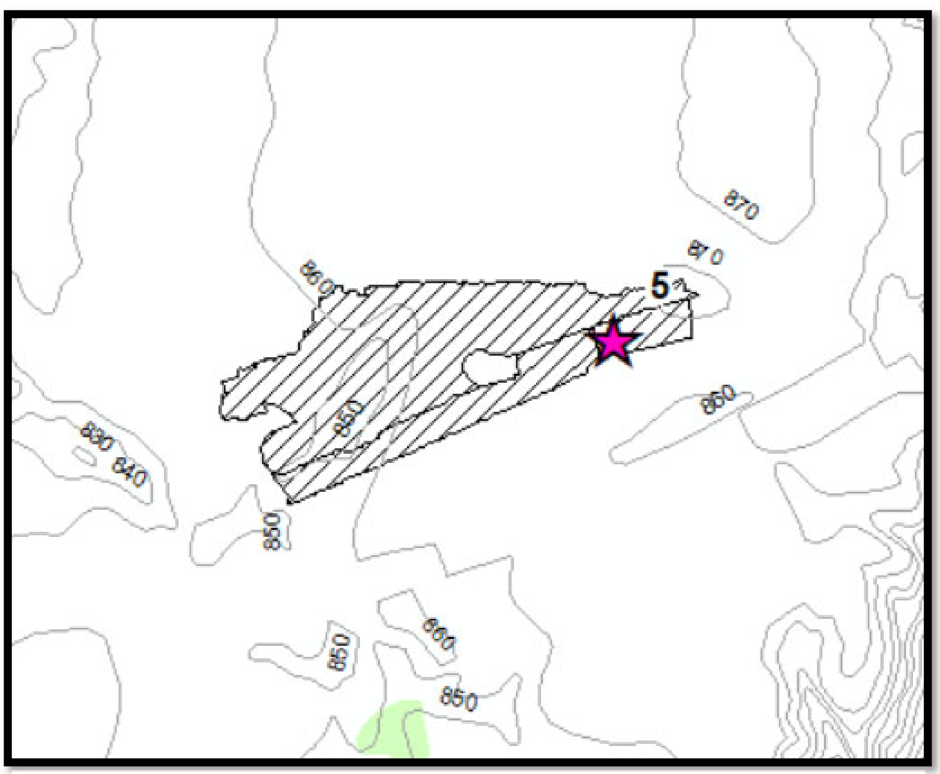
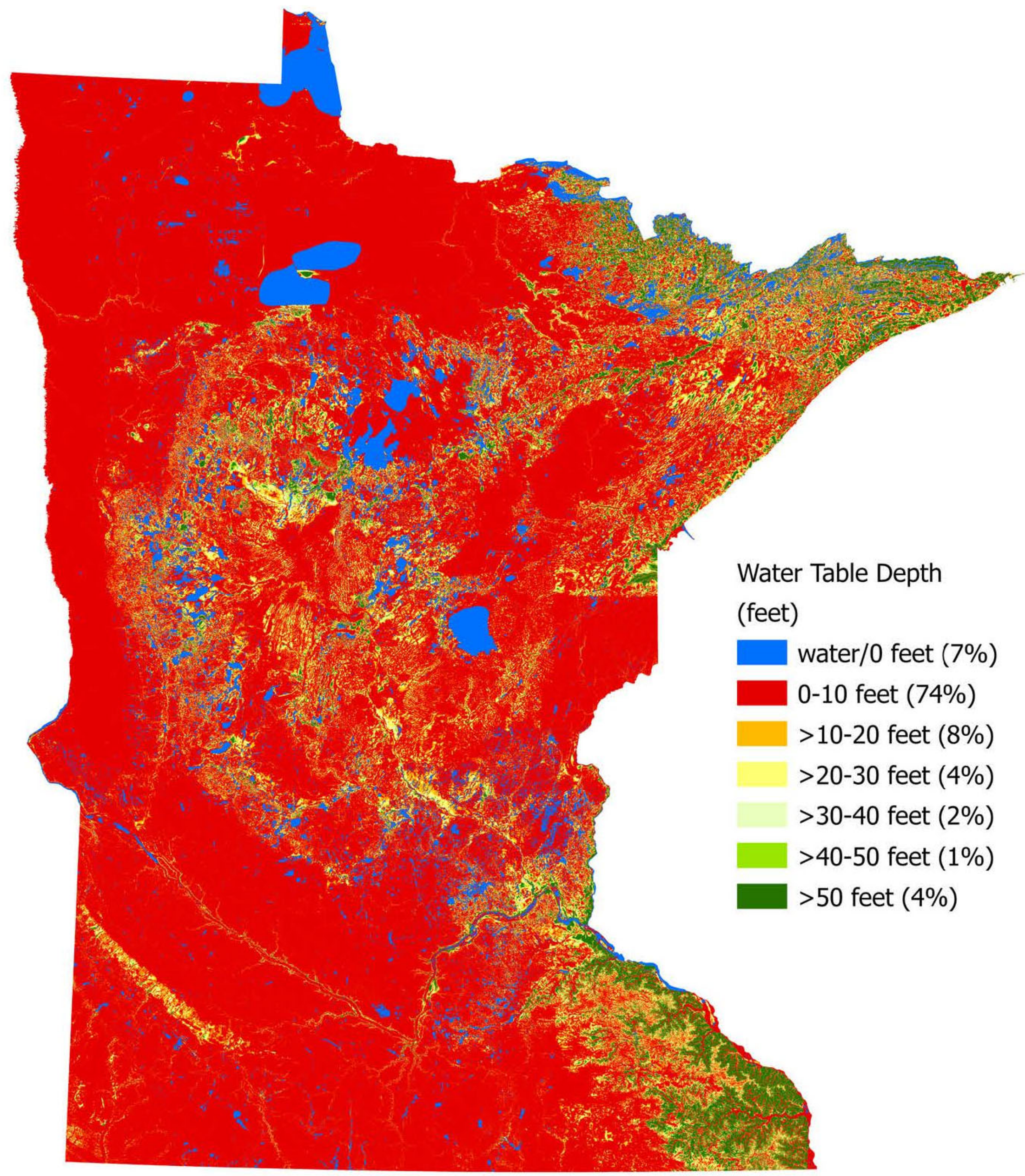


Figure 38: At site 5, the MGA identifies that the water table is 40 to greater than 50 feet deep. Few wetlands and other water table features are found in the nearby area and none in the project area.



Water-Table Elevation and Depth to Water Table, Minnesota Hydrogeology Atlas series HG-03

This dataset estimates the water-table elevation from three primary sources: depth to water table in saturated soils from Natural Resources Conservation Service data (which are converted to elevation), elevation of surface water bodies, and the static water elevation in water table wells with verified locations. With the use of a 30-meter DEM derived using LiDAR data, depth to water table is derived from the water-table elevation.

https://gisdata.mn.gov/dataset/geos-hydrogeology-atlas-hg03

Appendix D: Soils Interpretations from MN Rule 7080

7080.1110 Definitions (Most Relevant Excerpts)

Subp. 19. Distinct. "Distinct" means a soil color that is not faint as described in subpart 29.

Subp. 29. Faint. "Faint" means a soil color:

A. with the same hue as another soil color but that varies from the other color by two or less units of value and not more than one unit of chroma;

B. that differs from another soil color by one hue and by one or less units of value and not more than one unit of chroma; or

C. that differs from another soil color by two units of hue with the same value and chroma.

Subp. 59 Periodically Saturated Soil. "Periodically saturated soil" means the highest elevation in the soil that is in a reduced chemical state due to soil pores filled or nearly filled with water causing anaerobic conditions. Periodically saturated soil is determined by the presence of redoximorphic features in conjunction with other established indicators as specified in part 7080.1720, subpart 5, items E and F, or determined by other scientifically established technical methods or empirical field measurements acceptable to the permitting authority in consultation with the commissioner.

Subp. 65 Redoximorphic. "Redoximorphic features" means:

A. a color pattern in soil, formed by oxidation and reduction of iron or manganese in saturated soil coupled with their removal, translocation, or accrual, which results in the loss (depletion) or gain (concentration) of mineral compounds compared to the matrix color; or

B. a soil matrix color controlled by the presence of ferrous iron.

Redoximorphic features are described in part 7080.1720, subpart 5, item E.

Subp. 87 Topsoil. “Topsoil” means the natural, in-place organically enriched soil layer with a color value of less than 3.5.

7080.1720 Field Evaluation

E. Depth to the periodically saturated soil for new construction or replacement as determined by redoximorphic features and other indicators, as determined in subitems (1) to (3):

(1) in subsoil and parent material, redoximorphic features include:

(a) distinct redoximorphic iron accumulations or distinct redoximorphic iron depletions;

(b) a gleyed or depleted soil matrix or redoximorphic mottles having a color chroma of two or less or a depleted matrix or redoximorphic mottles having a color hue of 5Y and a chroma of three or less; or

(c) faint redoximorphic concentrations or faint redoximorphic depletions in subsoil or parent material with a hue of 7.5YR or redder;

(2) in lower topsoil layers that are deeper than 12 inches from the surface and are immediately followed in depth by a periodically saturated horizon, redoximorphic features include:

(a) soil colors with a redoximorphic chroma of two or less; or

(b) redoximorphic accumulations or depletions;

(3) in the upper 12 inches of the topsoil layer, if it is immediately followed by a periodically saturated horizon, the depth of seasonal saturation is determined by one or more of the indicators in units (a) to (f):

(a) soil colors with a chroma of zero;

(b) organic soil textures or mineral soil textures with an organic modifier;

(c) dominance of hydrophytic vegetation;

(d) the soil treatment area at or near the elevation of the ordinary high water level of a surface water or in a concave hill slope position;

(e) redoximorphic accumulation or depletions; or

(f) the soil expressing indicators of seasonal saturation as determined in Field Indicators of Hydric Soils in the United States: A Guide for Identifying and Delineating Hydric Soils, USDA Natural Resource Conservation Service (2006 and as subsequently amended). The field indicators are incorporated by reference, are available through the Minitex interlibrary loan system, and are subject to frequent change

Appendix E: Runoff Component Estimates

	acres	% area to study swale	Runoff Coeffecient	Estimated Effective Runoff Ratio	Acres x Effective Runoff Ratio	% of water to study swale watershed
Site 3						
Immediate Study Swale Area						
Road	0.22	6%	1	1	0.22	13%
Road-side swale/grass	0.37	11%	1	1	0.37	23%
Grass-side swale/grass	0.51	15%	1	1	0.51	31%
Upstream						
Road	0.66	19%	0.73	0.53	0.35	22%
Other Impervious	0.00	0%	0.73	0.53	0.00	0%
Road-side swale/grass	0.71	21%	0.3	0.1	0.07	4%
Grass-side swale/grass	0.97	28%	0.3	0.1	0.10	6%

	acres	% area to study swale	Runoff Coeffecient	Estimated Effective Runoff Ratio	Acres x Effective Runoff Ratio	% of water to study swale watershed
Site 4						
Immediate Study Swale Area						
Road	0.31	7%	0.73	0.73	0.22	15%
Road-side swale/grass	0.52	12%	1	1	0.52	35%
Grass-side swale/grass	0.30	7%	1	1	0.30	20%
Upstream						
Road	0.20	4%	0.73	0.53	0.10	7%
Other Impervious	0.12	3%	0.73	0.53	0.07	4%
Road-side swale/grass	1.84	42%	0.3	0.1	0.18	12%
Grass-side swale/grass	1.07	25%	0.3	0.1	0.11	7%

Reducing number for upstream contributions 0.2

Appendix F: Soil Profile Observations

Site 1 - Cross-section 1

Date:	10/14/2016	**Field Crew:**	Dave Bauer, PSS	**Station ID:**
Landscape Location:	Shoulder	**Slope & Aspect:**	North	**Pit I**
Parent Material:	Road fill	**Vegetation:**	Grasses	
Age of PM:		**General location:**	8 feet from road	
Distance from strea				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-15				Granular	18-25	L	10YR 3/2			
	15+				—		Gravel				Gravel (compacted rocks

Other notes:

Date:	10/14/2016	**Field Crew:**	Dave Bauer, PSS	**Station ID:**
Landscape location:	Shoulder	**Slope & Aspect:**	North	**Pit II**
Parent material:	Road fill	**Vegetation:**	Grasses	
Age of PM:		**General location:**	MN Road between weir 1 & 2; 14 feet from road	
Distance from strea	NA			
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-12				Granular	18-24	SCL	10YR 4/3			
	0-24				—	42+	SiC	10YR 2/1			10YR 5/2 mixed
	37				—	25-35	SiCL	10YR 5/2			2% 5YR 5/8 mottles
	82				—	~35	SiCL	10YR 3/1			
	96				Blocky	—	SCL	10YR 5/6			
	120+				Granular	18-25	L	10YR 5/6			

Other notes:

Date:	10/14/2016	**Field Crew:**	Dave Bauer, PSS	**Station ID:**
Landscape location:	Backslope	**Slope & Aspect:**	North	**Pit III**
Parent material:	Road fill	**Vegetation:**	Grass/Thistle	
Age of PM:		**General location:**	26 feet from road; Between weir 1 and weir 2	
Distance from strea				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-17				Granular	25-35	CL	10YR 3/3			
	34				—	38+	CL	10YR 3/1			Oxidized Rhizospheres 1%
	56				—	38+	CL	10YR 3/1	10YR 4/1 depletion 5% and Oxidized Rhizosp		
	70				—	25-35	CL	10YR 5/6			7.5YR 5/8 mottles 7%
	96				—	25-35	CL	10YR 5/6			

Other notes:

Date:		**Field Crew:**	David Bauer/Kellie Thom	**Station ID:**
Landscape Location:	Foot/Toe	**Slope & Aspect:**	North	**Pit IV**
Parent Material:	Fill	**Vegetation:**	Grass/Thistle	
Age of PM:		**General location:**	15 feet from fence	
Distance from strea				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-18					35-42	SCL	10YR 2/1	0		Wet soil-Top Layer
	18-36					42	SCL	10YR 2/1	0		
	36-52					42	SCL	10YR 4/1	0	Mottle 30% 7.5YR 5/6, 5G 5/1; 3	
	52-87+					25-35	CL	10YR 4/4	5		

Other notes:

Date:	10/18/2016	**Field Crew:**	David Bauer/Kellie Thom GIS	**Station ID:**
Landscape Location:	Back Slope	**Slope & Aspect:**	South Slope	**Pit V**
Parent Material:	Fill	**Vegetation:**	Grass	
Age of PM:	—	**General location:**	Between weir 1 and 2; 10 feet from fence	
Distance from strea				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-12				Granular	25-35	SiCL	10YR 2/2			
	23				—	42+	SiCL	10YR 2/2			5% 10YR 5/6-dense
	40				—	25-35	CL	10YR 4/3			2% 10YR 5/6 dense
	56				—	25-35	CL	10YR 4/3	↑i-??	15% 7.5YR 5/6-mixed more grave	
	64				Blocky	12-25	SL	10YR 4/4			Lots of clay pockets-wet
	84+				Blocky	12-25	SL	10YR 4/4			Lots of clay pockets-dry;

Other notes:

Date:	10/18/2016	**Field Crew:**	David Bauer/Kellie Thom	**Station ID:**
Landscape Location:		**Slope & Aspect:**		**Pit VI**
Parent Material:		**Vegetation:**		
Age of PM:		**General location:**		
Distance from strea				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-15				Granular	25-35	SiCL	10YR 3/2			worm activity
	15-33				Granular	18-25	SiL	2.5YR 5/3			Mottle 7.5YR 4/6, 25%
	33-79				Blocky	18-25	SiCL	2.5YR 5/4			Mottle 7.5YR 5/6, 7%

Other notes:

Site 1 - Cross-section 2

3	10/18/2016	**Field Crew:**	David Bauer/Kellie Thom	**Station ID:**
Landscape Location:	Inslope Shoulder	**Slope & Aspect:**		Pit i
Parent Material:	Fill	**Vegetation:**	Grass/Weeds	
Age of PM:		**General location:**	Shoulder of Road	
Distance from strear				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-22					25-30	SiSCL	10YR 4/2	5		NA
	22-55					0-8	LS	10YR 4/4	5		NA
											Hit road bed at 55 cm

Other notes:

Date:	10/18/2016	**Field Crew:**	David Bauer/Kellie Thom	**Station ID:**
Landscape Location:	Inslope	**Slope & Aspect:**		Pit ii
Parent Material:		**Vegetation:**	Grass/Weeds	
Age of PM:		**General location:**		
Distance from strear				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-10					25-30	SiCL	10YR 3/2			NA
	10-20					25-30	SiCL	10YR 2/2			Redox 10YR 4/6 1%
	20-50					0-8	Lsa	10YR 3/4			Redox but hard to
	50-63					42+	C	10YR 4/4			Mottle 10YR 5/6 1%

Other notes:

Date:	10/18/2016	**Field Crew:**	David Bauer/Kellie Thom	**Station ID:**
Landscape Location:	Toe of Inslope	**Slope & Aspect:**		Pit iii
Parent Material:	Fill	**Vegetation:**	Grasses/Weeds	
Age of PM:		**General location:**		
Distance from strear				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-15					25-35	CL	10YR 3/1			
	15-37					25-35	CL	10YR 5/4			Dep. Gleyl 10YR 5/1 3%;
	37-65					25-35	CL	10YR 5/4			Redox 7.5YR 4/6 15%;
	65-75					18-25	SiCL	10YR 5/4			No Depl.; Redox 7.5YR 5/8 30%

Other notes:

Date:	10/18/2016	**Field Crew:**	David Bauer/Kellie Thom	**Station ID:**
Landscape Location:	Toe of Backslope	**Slope & Aspect:**		Pit iV
Parent Material:		**Vegetation:**	Grasses and Weeds	
Age of PM:		**General location:**		
Distance from strear				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-12					25-35	SiCL	10YR 2/1			
	12-20					25-35	CL				Unable to color due to high mositure--ve
	20-33					25-35	CL	2.5YR 5/3			Mottle 7.5YR 4/4--
	33-79	50%				18-25	SiL	10YR 5/1			
	33-79	50%				18-25	SiL	10YR 5/8			

Other notes:

Date:	10/18/2016	**Field Crew:**	David Bauer/Kellie Thom	**Station ID:**
Landscape Location:	Backslope Midslope	**Slope & Aspect:**		Pit V
Parent Material:		**Vegetation:**	Grasses and Weeds	
Age of PM:		**General location:**		
Distance from strear				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-21					25-35	SiCL	10YR 3/2			Worm Activity
	21-35					25-35	CL	2.5YR 5/3			Mottle 5YR 4/6 1%

Other notes:

Date:	10/18/2016	**Field Crew:**	David Bauer/Kellie Thom	**Station ID:**
Landscape Location:	Backslope Top	**Slope & Aspect:**		Pit Vi
Parent Material:		**Vegetation:**	Grass/Weeds	
Age of PM:		**General location:**		
Distance from strear				
			MPCA Correction Factor:	

Horizon	Depth cm	Boundry	Structure size	Structure grade	Structure type	% clay	texture	color	gravel %	eff	redox. & other
	0-15					18-25	SiL	10YR 3/2			Worm Activity
	15-35					18-25	L	2.5YR 5/3			Mottle 5YR 3/4 1%
	35-63				Granular	18-25	L	2.5YR 5/3			Mottle 7.5YR 5/6 20%

Other notes:

Site 2, Cross-section 1

Soil Pit:	1-1				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-9	10YR 2/2	loam	medium blocky		plant roots, compacted
9-20	2.5Y 4/4	clay loam	coarse blocky	7% faint dep & mtl	compacted
20-32	10YR 2/2	silt loam	3% 10Y 7/1 (gley) dep, faint mtl		
32-41	2.5Y 4/3	silt loam		15% 10Y 7/1 (gley) dep, 10% 10YR 5/6 mtl	

Soil Pit:	1-2				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-5	10YR 3/2	loam			plant roots, compacted
5-9	10YR 4/4	sandy clay loam			7% coarse stones & gravel
9-17	10YR 3/2	loam		7% faint mtl	
17-26	2.5Y 4/3	clay loam	20% 7.5YR 4/4 mtl, 20% 5Y 4/1 dep		
26-39	2.5Y 4/3	clay loam	5% 7.5YR 4/4 mtl, 10% 5Y 6/1 dep		
39-42	10YR 3/1	clay			

Soil Pit:	1-3				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-6	10YR 3/2	silt loam	granular		Roots
6-17	10YR 3/3	silt clay loam	coarse blocky	3% faint	Compacted
17-22	10YR 3/2	clay		7% 5YR 4/6; 10% 5Y 6/1 dep	Compacted; Roots
22-38	10YR 2/1	clay		5% faint mtl	Compacted

Soil Pit:	1-4				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-8	10YR 2/2	silt clay	blocky		Compacted; Roots
8-19	10YR 3/2	silt clay		7% 10YR 4/6 mtl	Mottles follow old root channels and continuous; Compacted
19-38	10YR 2/1	clay		10% 10YR 4/1 dep (gley)	Compacted; Roots

Soil Pit:	1-5				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-6	10YR 3/2	loam	medium granular		Roots
6-11	10YR 4/4	loamy sand	medium granular		
11-21	10YR 4/3	clay loam	coarse granular		Compacted
21-38	10YR 5/2	clay loam	7% 7.5Y 5/6 mtl; 10% 10YR 6/1 De		Compacted

Soil Pit:	1-6				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-4	10YR 3/1	loam	medium granular		Roots; Light compaction
4-15	7.5YR 3/4	loam sand	medium granular		
15-22	10YR 4/4	clay	coarse blocky	5% faint dep	
22-27	2.5Y 5/4	clay	coarse blocky	2% faint mtl	Very compact; Dry; Possible Carbonates
27-34	10YR 5/3	clay	2% 7.5YR 5/8 mtl; 5% 2.5Y 5/2 de		Very compact; Possible Carbonates

Site 2, Cross-section 2

Soil Pit:	3-1				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-6	10YR 2/3	loam	medium granular	none	
6-21	10YR 3/4	loamy sand	fine granular	none	

Soil Pit:	3-2				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-6	10YR 2/2	silt loam	medium granular		Root
6-11	10YR 3/3	loamy sand	medium granular		
11-24	10YR 3/2	clay		15% 5YR 3/4 mtl	Compacted
24-38	10YR 2/1	clay loam		5% 5GY 5/1 dep; 3% 10YR 4/8 mtl	Compacted

Soil Pit:	3-3				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-4	10YR 2/2	silt loam	medium granular		
4-11	10YR 3/2	silt clay loam		10% 7.5YR 5/8 mtl	Compacted
11-26	10YR 3/1	clay loam		15% 7.5YR 4/6 mtl	Compacted
26-32	2.5Y 4/3	clay		20% 10Y 5/1 dep; 15% 7.5YR 5/6 mtl	Compacted
32-38	10YR 3/1	clay loam		5% 10YR 4/6 mtl; 7% 10Y 6/1 dep	

Soil Pit:	3-4				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-5	10YR 2/2	clay loam	medium granular		
5-14	10YR 3/2	clay loam		7% 7.5YR 5/8 mtl	Compacted
14-21	10YR 3/2	clay loam		30% 5YR 3/4 mtl	Compacted
21-40	2.5Y 4/4	clay loam		5% 10YR 5/6 mtl; 10% 5YR 5/2 dep	Compacted

Soil Pit:	3-5				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-7	10YR 2/2	silt loam	medium granular		
7-24	10YR 3/2	silt clay loam	coarse blocky	15% 7.5YR 5/6 mtl; 7% faint dep	Compacted
24-35	10YR 2/1	clay	coarse blocky	2% 5YR 3/4 mtl	Compacted

Soil Pit:	3-6				
Depth (in)	Color	USDA Texture	Structure	Redox	Other
0-8	10YR 3/2	loam	medium granular		
8-14	10YR 4/4	sandy loam	medium granular		
14-29	2.5Y 4/3	clay loam	medium blocky	2% - 15% faint mtl & dep	Compacted
29-38	10YR 2/1	silty clay			Compacted

Site 3, Cross-section 1

Soil Pit:	1-1			MPCA Correction Facto 2.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-2"	10YR 3/2	Sandy Loam	Granular	0	A lot of Roots
2"-18"	10YR 2/2	Clay	Blocky	5YR 4/6 10%	Very Compacted/fill
18"-22"	10YR 4/6	Sand	Granular	0	
22"-32"	2.5Y 5/3	Silty Clay		7.5 YR 4/6 5%	Depletion and clay mixed in

Soil Pit:	1-2			MPCA Correction Facto 2.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-2"	10YR 3/2	Sandy Loam	Granular	0	A lot of Roots
2"-22"	10YR 2/1	Clay	Blocky	5YR 4/6 5%	Fill/very Compact. 2 Colors in Matrix
2"-22"	10YR 4/4	Clay	Blocky		15% of Matrix
22"-28"	2.5Y 5/2	Silty Clay		7.5YR 6/8 15%	Very Compact

Soil Pit:	1-3			MPCA Correction Facto 2.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-2"	10YR 3/2	Clay Loam	Blocky	0	Root Layer
2"-24"	10YR 2/1	Clay	Blocky		
2"-24"	2.5Y 5/3	Silty Clay	Blocky	Various 20%	

Comment: Mottles in fill soils may have been imported to site during construction.

Soil Pit:	1-4			MPCA Correction Facto 2.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-3"	10YR 3/2	Clay Loam	Blocky	0	Root Layer
3"-8"	10YR 2/1	Clay	Blocky		
3"-8"	10YR 3/2	Clay	Blocky	faint 2%	
8"-25"	2.5Y 4/3	Silty Clay	Blocky	Depth 2.5Y 6/2 10%. Mottles 2.5Y 6/8 10%	

Soil Pit:	1-5			MPCA Correction Facto 2.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-3"	10YR 2/2	Clay Loam	Granular	0	Root Layer
3"-9"	2.5Y 3/2	Clay Loam	0	7.5YR 5/8 30%	Mottles
9"-15"	10YR 2/1	Silty Clay	0	7.5YR 5/8 5%	Mottles - Old Cattail
15"-27"	2.5Y 4/2	Clay Loam	0	10YR 5/8 30%	Redox
27"-31"	10YR 2/1	Clay	Blocky	5GY 6/1	(Gley) 10%

Soil Pit:	1-6			MPCA Correction Facto 2.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-6"	10YR 3/1	Clay Loam	Granular	Faint 3%	10YR 5/2 (Second Matrix)
6"-12"	10YR 4/2	Silty Clay	0	Faint 5%	5% Organics
12"-25"	10YR 4/2	Clay Loam	0	7.5YR 5/8 5%	15% 10YR 2/1
25"-29"	10Y 6/1 Gley	Sandy Loam	0		

Soil Pit:	1-7			MPCA Correction Facto 2.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-6"	10YR 3/2	Clay Loam	Granular	0	
6"-17"	10YR 2/1	Clay Loam	0	Faint 2%	
6"-17"	2.5Y 5/3		0		
17"-29"	10YR 4/4	Silty Clay Loam	0	7.5YR 5/8 1% - Mottles	2.5YR 3/6 7%

Site 3, Cross-section 2

Soil Pit:	3-1			MPCA Correction Factor:	2.5
Depth	**Color**	**USDA Texture**	**Structure**	**Redox**	**Other**
0-13"	10YR 3/1	Silty Clay Loam	0	20% 5YR 4/6	Mixed
13"-19"	10YR 4/4	Silty Clay Loam	0	1% Faint Mottles	

Soil Pit:	3-2			MPCA Correction Factor:	6.5
Depth	**Color**	**USDA Texture**	**Structure**	**Redox**	**Other**
0-4"	10YR 3/2	Sandy Loam	Blocky	0	Very Compact. 10% Gravel

Comment: Soil was too compact to get a profile.

Soil Pit:	3-3			MPCA Correction Factor:	3.5
Depth	**Color**	**USDA Texture**	**Structure**	**Redox**	**Other**
0-7"	10YR 2/2	Sandy Clay Loam	Blocky	0	Compacted
7"-19"	10YR 4/4	Sandy Clay Loam	0	7% Dep 2.5Y 6/1	1% Mottles 7.5YR 6/8
19"-23"	10YR 4/4	Sandy Clay Loam	Granular	0	Not Compacted. 5% Gravel
Gravel @ 23"					

Soil Pit:	3-4			MPCA Correction Factor:	2.5
Depth	**Color**	**USDA Texture**	**Structure**	**Redox**	**Other**
0-12"	10YR 3/2	Silty Clay	Blocky	Depth 10% Faint	Mottles 15% Compacted
12"-16"	10YR 2/1	Clay	0	5YR 4/6 7%	Compact Mixed Mottles and Depletions
16+ Gravel					

Comment: Hit Rock Layer

Soil Pit:	3-5			MPCA Correction Factor:	2.5
Depth	**Color**	**USDA Texture**	**Structure**	**Redox**	**Other**
0-4"	10YR 4/3	Clay Loam	Granular	7% Faint Redox.	
4"-15"	10YR 3/2	Clay Loam	Blocky	5% Depth. 7% Faint Mottles	
15"-19"	10Y 6/1 Gley	Silty Clay	0	10YR 6/8 30%	3% Gravel
19"-28"	2.5Y 4/4	Sandy Loam	Granular	Faint Redox. 2%	Clay Inclusions (see above) for Redox Gravel

Soil Pit:	3-6			MPCA Correction Factor:	2.5
Depth	**Color**	**USDA Texture**	**Structure**	**Redox**	**Other**
0-7"	10YR 2/2	Silty Clay	Granular	5YR 5/8 3%	
7"-13"	10YR 2/1	Clay	0	5YR 4/6 7%	Compact Mixed Mottles and Depletions
7"-13"	10YR 4/2	Clay	0	5YR 4/6 7%	30% Gravel
13"-22"	10YR 4/4	Sandy Clay Loam	Blocky		10% 2.5YR 4/8

Soil Pit:	3-7			MPCA Correction Factor:	3.5
Depth	**Color**	**USDA Texture**	**Structure**	**Redox**	**Other**
0-7"	10YR 3/3	Sandy Clay Loam	Granular		Roots/Compacted
7"-12"	10YR 4/4	Silty Clay Loam	Blocky	Faint 5%	Compact
12"-14"					Field Rock
14"-22"	10YR 4/4	Sandy Clay Loam	Blocky	5% 5YR 5/8	7% 2.5YR 4/8. 30% Gravel. Native Soil

Site 4, Cross-section 1

Soil Pit:	1-1			MPCA Correction Factor 6.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-3"					asphalt and class 5
3"-12"	10YR 2/2	SL	granualar	none	class 5 mixed in
12"-23"	10YR 4/4	CL	blocky	very faint mottles, 5%	

Soil Pit:	1-2			MPCA Correction Factor 6.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-7"	10YR 2/2	SL	granular	none	
7"-9"				none	broken-up asphalt and sand
9"-22"	10YR 4/4	CL	0	none	
22"-27"	10YR 4/4	SiC	0	7% mtls, 7.5YR 5/8	

Soil Pit:	1-3			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-5"	10YR 2/2	L	granual	none	High Organics
5"-8"	10YR 4/3	SCL	blocky	2% faint mottles	
8"-19"	10YR 4/6	CL	blocky	2% faint depletions & mottles	shale at 12"

Soil Pit:	1-4			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-6"	10YR 3/2	L	granular	none	many roots
6"-21"	10YR 3/3	CL	blocky	15% 7.5YR 4/6 mottles	30% depletions and Crovina
21"-30"	2.5Y 4/4	CL	0	20% 7.5YR 4/6 mottles	25% gravel

Soil Pit:	1-5			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-7"	10YR 2/2	SiL	granular	none	
7"-24"	10YR 4/3	SiL	blocky	3% faint mottles	

Soil Pit:	1-6			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-4"	10YR 3/2	silt loam	granular	none	many roots
4"-12"	10YR 4/3	silty clay loam	blocky	7% 5YR 4/6 mottles	compacted, dense
12"-20"	10YR 4/4	clay	0	15% 5YR 4/6 mottles	dense
20"-26"	10YR 4/4	clay	0	5% 5YR 5/6 mottles	5% gravel

Soil Pit:	1-7			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-5"	10YR 3/3	silt loam	granular	none	fiberous
5-17"	10YR 4/6	clay loam	blocky	none	7-11" compacted
17-27"	2.5Y 2/3	clay	blocky	15% 5YR 4/6 mottles	dense layer

Site 4, Cross-section 2

Soil Pit:	5-1			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-7"	10YR 2/2	0-silt loam	granular	none	
7-13"	10YR 4/4	silt clay	blocky	2.5YR 3/6 7% PL	Depletions 5G 4/2 (gley)
13-21"	10 YR 3/3	silt clay loam	blocky	15% 5YR 3/4	sand towards bottom
21-29"	7YR 3/4	sandy loam	blocky	50% -->	Redox and depletions
21-29"	10 4/4	sandy loam			50%

Soil Pit:	5-2/5-3 (very close)			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-4"	10YR 2/2	0-silt loam	granular	0%	
4-10"	10YR 3/3	clay	blocky	20%	faint mottles/dep. 5% gravel
10-14"	10YR 3/3	sandy clay loam	blocky	5% 5YR 3/4	
14-20"	10YR 4/4	sandy clay loam	blocky	5% 5YR 4/6	10gy 5-1(Gley) 7% dep
20-30"	10YR 3/4	sandy clay loam	blocky	2.5YR 3/6 5%	5g 5/1 (gley) 30% dep

Soil Pit:	5-4			MPCA Correction Factor 6.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-7"	10YR 3/3	sandy loam	granular	none	
7-18"	10YR 3/4	sandy loam	granular	very faint mottles	
18-30"	10YR 3/4	sandy loam	granular	very faint mottles	very narrow band of clay = inclusion
30-33"	10YR 3/6	sandy clay loam	blocky	faint mottles	5G1 6/1 2%dep

Soil Pit:	5-5			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-7"	10YR 2/2	loam	granular	none	
7-19"	10YR 3/3	sandy loam	too moist	none	
19-25"	10YR 4/4	sandy loam	granular	very faint mottles	

Soil Pit:	5-6			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-5"	10YR 3/3	silt loam	granular	none	
5-12"	10YR 4/4	sandy loam	blocky	2%	faint mottles and ox rnz.
12-17"	10YR 4/4	clay loam	blocky	5% 2.5YR 3/6	7% shale
17-27"	10YR 3/4	clay	blocky	5% 2.5YR 3/6	

Soil Pit:	5-7			MPCA Correction Factor 4.5	
Depth	Color	USDA Texture	Structure	Redox	Other
0-8"	10YR 3/3	loam	granular	none	
8-18"	7.5YR 4/6	clay loam	blocky	none	
18-28"	10YR 4/4	clay loam	blocky	1%	5YR 4/6 mottles

Site 5, Cross-section 1

Soil Pit:	1-1	MPCA Correction Factor 3.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-6"	10YR 3/3	Sandy Loam	0	none	very compacted
6" - 16"	10YR 3/4	Loamy Sand	0	none	very compacted

Soil Pit:	1-2	MPCA Correction Factor 3.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-5"	10YR 2/2	Sandy Loam	0	none	very compacted, could not penetrate deeper by using hand tools.

Soil Pit:	1-3	MPCA Correction Factor 2.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-7"	10YR 3/2	silt loam	0	none	very compacted
7" - 14"	10YR 3/3	loamy sand	0	none	loose

Soil Pit:	1-4	MPCA Correction Factor 2.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0 - 7.5"	10YR 2/2	loam	0	none	very compacted, could not penetrate deeper by using hand tools.

Soil Pit:	1-5	MPCA Correction Factor 2.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-12"	10YR 2/2	loam	0	none	very compacted
12" - 15"	10YR 2/2	loam	blocky	Depletions 10YR 4/6	compacted
15" - 23"	10YR 3/3	loamy sand	0	none	

Soil Pit:	1-6	MPCA Correction Factor 2.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-2"	10YR 2/2	silty clay loam	granular	none	sod layer
2" - 10"	10YR 2/2	silty clay loam	0	none	
10" - 21"	10YR 3/3	loamy sand	0	none	loose

Soil Pit:	1-7	MPCA Correction Factor 2.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-3"	10YR 2/2	loam	granular	none	compacted
3" - 11"	10YR 2/2	loam	0	none	compacted
11" - 13"	10YR 2/2	loamy sand	0	none	loose / large rock 40%
13" - 16"	10YR 3/3	loamy sand	0	none	loose

Site 5, Cross-section 2

Soil Pit:	3-1	MPCA Correction Factor 3.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-1"	10YR 3/2	sandy loam	granular	none	very compacted
1"-7"	10YR 3/2	sandy loam	0	5% mottles 10YR 6/6	

Soil Pit:	3-2	MPCA Correction Factor 3.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-1"	10YR 3/3	sandy loam	granular	none	very compact, vegetation layer
1"-12"	10YR 3/3	sandy loam	blocky	none	very compact
12"-17"	10YR 3/3	loamy sand	0	none	loose, seems like fill soil

Soil Pit:	3-3	MPCA Correction Factor 3.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-2"	10YR 2/2	loam	0	none	very compacted, vegetation layer
2"-12"	10YR 2/2	sandy loam	blocky to 0	none	very compacted, mixed layer

Soil Pit:	3-4	MPCA Correction Factor 3.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-10"	10YR 2/2	sandy loam	0	none	very compacted, roots very shallow

Soil Pit:	3-5	MPCA Correction Factor 2.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-1"	10YR 2/2	loam	0	none	very compact, sod
1"-10"	10YR 2/2	loam	0	none	very compact

Soil Pit:	3-6	MPCA Correction Factor 2.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-1"	10YR 2/2	loam	granular	none	very compact, sod
1"-15"	10YR 2/2	loam	0	none	very compact
15"-26"	10YR 3/4	sand	0	none	loose

Soil Pit:	3-7	MPCA Correction Factor 2.5			
Depth	Color	USDA Texture	Structure	Redox	Other
0-3"	10YR 2/2	loam	granular	none	compact, sod
3"-20"	10YR 2/2	loam	blocky	none	compact
20"-27"	10YR 3/4	loam	0	none	loose

Soil Observation Interpretation Key

(tan swatch)	=	topsoil color without indicators of seasonally saturated soils noted
(gray-blue swatch)	=	topsoil color with color-based indicators of seasonally saturated soils
(pale blue swatch)	=	Possibly seasonally high water table based on notes, but mottling colors were not noted and therefore cannot confirm (top or sub soil)
(pale yellow swatch)	=	subsoil color without indicators of seasonally saturated soils noted
(blue swatch)	=	Subsoil color with indicators of seasonally saturated soils
(red swatch)	=	observation location at toe of slope/swale bottom
(pink swatch)	=	gravel/rock
(yellow swatch)	=	other interesting observations (often compaction)

Appendix G: Restrictive Soil Texture Analysis

Site	Station ID	Most Restrictive Layer w/in 3 feet of bottom	Depth (cm for Site 1 in for others)	Clay Content *	HSG based on Soil Texture	Comment
Site 1	Pit I	Loam	0-15	18-25%	D	High clay contenct expect infiltration similar to CL-ML
	Pit II	Silty Clay	0-24	42%+	D	Clayey soils with ≥ 18% Clay below
	Pit III	Clay	17-56	38%+	D	High clay content in all layers
	Pit IV	Silty Clay Loam	18-52	42%	D	Other layers have high similarly high clay content.
	Pit V	Silty Clay Loam	12-23	42%+	D	High clay content in all layers near surface
	Pit VI	Silty Clay Loam	0-15	25-35%	D	
	Pit i	Silty Sandy Clay Loam	0-22	25-35%	D	Less restrictive below
	Pit ii	Silty Clay Loam	0-20	25-35%	D	Less restrictive below
	Pit iii	Clay	0-65	25-35%	D	High clay content in all layers to
	Pit iv	Clay	12-33	25-35%	D	High clay content in all layers to
	Pit v	Clay	12-35	25-35%	D	Similar clay content layer above
	Pit vi	Silt Loam	0-15	18-25%	D	Similar clay content layers below. Clay content high for silt loam
Site 3	Site 1-1	Clay	2-18	30-100%	D	Notes say very compacted, granular sand layer at 18-22"
	Site 1-2	Clay	2-22	30-100%	D	Clay content 10-14% in soil below
	Site 1-3	Clay	2-24	30-100%	D	Clay content 10-14% in soil below
	Site 1-4	Clay	8-24	30-100%	D	Clay content 10-14% in soil below
	Site 1-5	Clay Loam	0-9	27-40%	D	Other layers within 31-inched of surface have clay 10% or more
	Site 1-6	Clay Loam	0-6, 12-25	27-40%	D	Potentially less restrictive soil at depth 25" (SL)
	Site 1-7	Clay Loam	0-17	27-40%	D	
	Site 3-1	Silty Clay Loam	0-19	27-40%	D	
	Site 3-2	Sandy Loam	0-4	0-20%	D	HSG based on compaction. Very Compacted, only 4-inch depth
	Site 3-3	Sandy Clay Loam	0-23	20-35%	D	Gravel below
	Site 3-4	Clay	12-16	30-100%	D	Gravel below
	Site 3-5	Clay Loam	0-15	27-40%	D	Granular material (SL) at 19-28 inch depth
	Site 3-6	Clay	7-13	30-100%	D	High clay content in soils below (SCL) to 22"
	Site 3-7	Silty Clay Loam	7-12	27-40%	D	
Site 4	Site 1-1	Clay Loam	12-23	27-40%	D	Upper layer potentially less restrictive (SL)
	Site 1-2	Clay Loam	9-22	27-40%	D	Upper layers potentially less restrictive (SL)
	Site 1-3	Clay Loam	8-19	27-40%	D	
	Site 1-4	Clay Loam	6-30	27-40%	D	
	Site 1-5	Silt Loam	0-24	0-27%	~C	HSG C if actually clay content <5%, otherwise HSG D
	Site 1-6	Clay	4-12	30-100%	D	
	Site 1-7	Clay	17-27	30-100%	D	
	Site 5-1	Silt Clay Loam	13-21	27-40%	D	
	Site 5-2/5	Clay	4-10	30-100%	D	
	Site 5-4	Sandy Clay Loam	30-33	20-35%	D	Less restrictive soils above (SL) , 0-30", Clay 0-20%
	Site 5-5	Loam	0-7	7-27%	D	Possibly HSG C if a silt loam (essentially no clay content)
	Site 5-6	Clay	12-17	30-100%	D	
	Site 5-7	Clay Loam	8-28	27-40%	D	
Site 5 **	Site 1-1	Sandy Loam	0-6	0-20%	~ B	HSG B if actual clay < 7%. Less restrictive soil below to 16" (LS)
	Site 1-2	Sandy Loam	0-5	0-20%	~ B	HSG B if actual clay < 7%.
	Site 1-3	Silt Loam	0-7	0-27%	~ C	HSG C if actually clay content <5%, otherwise HSG D
	Site 1-4	Loam	0-7.5	7-27%	- D	
	Site 1-5	Loam	0-15	7-27%	- D	
	Site 1-6	Silty Clay Loam	0-10	27-40%	D	Less restrictive soils (LS) below to 21"
	Site 1-7	Loam	0-11	7-27%	- D	
	Site 3-1	Sandy Loam	0-7	0-20%	~ B	HSG B if actual clay < 7%. Less restrictive soil below to 16" (LS)
	Site 3-2	Sandy Loam	0-12	0-20%	~ B	HSG B if actual clay < 7%.
	Site 3-3	Loam	0-2	7-27%	- D	Possibly HSG C if a silt loam (essentially no clay content)
	Site 3-4	Sandy Loam	0-10	0-20%	~ B	HSG B if actual clay < 7%.
	Site 3-5	Loam	0-10	7-27%	- D	Possibly HSG C if a silt loam (essentially no clay content)
	Site 3-6	Loam	0-15	7-27%	- D	Possibly HSG C if a silt loam (essentially no clay content)
	Site 3-7	Loam	0-27	7-27%	- D	Possibly HSG C if a silt loam (essentially no clay content)

* = clay content only recorded in site 1 soil boring, other clay content is based on typical NRCS soil definitions

~ = potential least restrictive class

\- = most likely the soil is D classification based on unlikeliness that the soil has essentially no clay content

** = All site 5 sites borings include notes about compaction

resourceful. naturally.
engineering and environmental consultants

BARR

DRAFT Technical Memorandum

To: David Fairbairn, Minnesota Pollution Control Agency (MPCA)
From: Greg Wilson, Barr Engineering Co. (Barr)
Subject: Stormwater Swales Infiltration Performance Assessment
Date: November 30, 2020
Project: 23621252.00

1.0 Background

The Minnesota stormwater management and regulatory community needs to understand the potential infiltration quantities within functioning roadside swales based upon various soil, hydrologic, and other conditions. Recent research studies conducted by several organizations have begun to fill in some of the knowledge gaps, but overall, few field studies of swale performance in a broad range of Minnesota conditions and timescales have been completed. There is significant motivation from a variety of sectors within Minnesota to develop this understanding.

MPCA and MNDOT developed and prototyped a field study of swale infiltration in 2016 at a single site. This study supported implementation of full-scale monitoring at several MN swales between 2017 and 2019. The purpose of this memorandum is to assist MPCA in achieving the primary project goal of quantifying estimates of volume reduction by swales on annual- and event-scales and across different site conditions by:

- Compiling/reviewing and performing quality assessments of monitoring data and flow analyses
- Executing modeling tasks for water balance estimation and results comparisons
- Reviewing and assisting with results interpretation and reporting.

2.0 Study Areas and Site Characteristics

Five total sites have been monitored across four study areas, with one area (MNROAD) being split into two non-adjacent sites on two nearby roads. The attached mapbook shows the delineated drainage areas for each site, including locations of V-notch weir monitoring installations that provided the necessary stage/flow monitoring data. Surveys were completed at each site to supply topographic and weir elevations, as well as Modified Philip-Dunne (MPD) falling head infiltrometer measurements to provide soil infiltration rate estimates for each swale section.

Topographic survey data was combined with LiDAR data in GIS to delineate the drainage areas directly tributary to the weir at each swale site. GIS was also used to delineate the impervious and pervious land segments directly tributary to each weir. The pervious land segments were then intersected with the SSURGO soils coverage to determine the relative area associated with each hydrologic soil group (HSG).

Table 2-1 summarizes the land segment type, predominate HSG and areas directly tributary to each weir location at each monitoring site. The drainage areas associated with each upstream weir are also tributary to the downstream weir.

Table 2-1 Land segment areas directly tributary to each monitoring site/weir location

Study Area	Weir Location	Land Segment Type	HSG	Drainage Area (acres)
Site 3—TH212	Upstream	Road	--	0.660
		Roadside swale slope	B	0.714
		Remaining pervious area	B	0.970
	Downstream	Road	--	0.216
		Roadside swale slope	B	0.372
		Remaining pervious area	B	0.505
Site 4—TH8	Upstream	Road	--	0.196
		Roadside swale slope	B	1.840
		Remaining pervious area	B	1.068
		Driveway and buildings	--	0.123
	Downstream	Road	--	0.306
		Roadside swale slope	B	0.523
		Remaining pervious area	B	0.303

3.0 Monitoring Data and Analysis

Rainfall and channel flow/stage monitoring was completed at each study area to quantify the primary water balance parameters that determine volume reduction by swales on an event- and annual basis. Tipping bucket rainfall gages were installed at each study area. Any gaps in rainfall monitoring data were supplemented with local climate records.

There are different v-notch discharge equations that can be applied to stage measurements in highway swales. The Cone Equation has historically been used for v-notch weirs with fully contracted flow as follows:

$$Q = 2.49\ h_1^{2.48}$$

where:

- Q = discharge over weir in ft3/s
- h1 = head on the weir in ft

Continuous stage measurements collected at the upstream side of each weir during each monitoring period were converted to head on the weir based on a comparison of survey measurements that determined the stage corresponding with zero head on the weir. This resulted in a continuous record of

flow measured at each weir site which was used to calculate the surface flow volumes during the 2018 and 2019 monitoring seasons. Cumulative flow volumes were calculated for each site between May and October of each season to avoid the uncertainty associated with snowmelt runoff from April snowfall events. Cumulative flow volumes were also plotted and compared, both upstream/downstream and against the cumulative rainfall volumes measured at each site, to provide quality checks on the monitoring data.

Figures 3-1 through 3-3 provide the monitoring results from 2018, while Figures 3-4 through 3-6 provide the 2019 monitoring results for each set of weir measurements collected at Site 3—TH212. Figures 3-7 through 3-9 provide the monitoring results from 2018, while Figures 3-10 through 3-12 provide the 2019 monitoring results for each set of weir measurements collected at Site 4—TH8.

Figure 3-1. Discharge Hydrograph, May- October

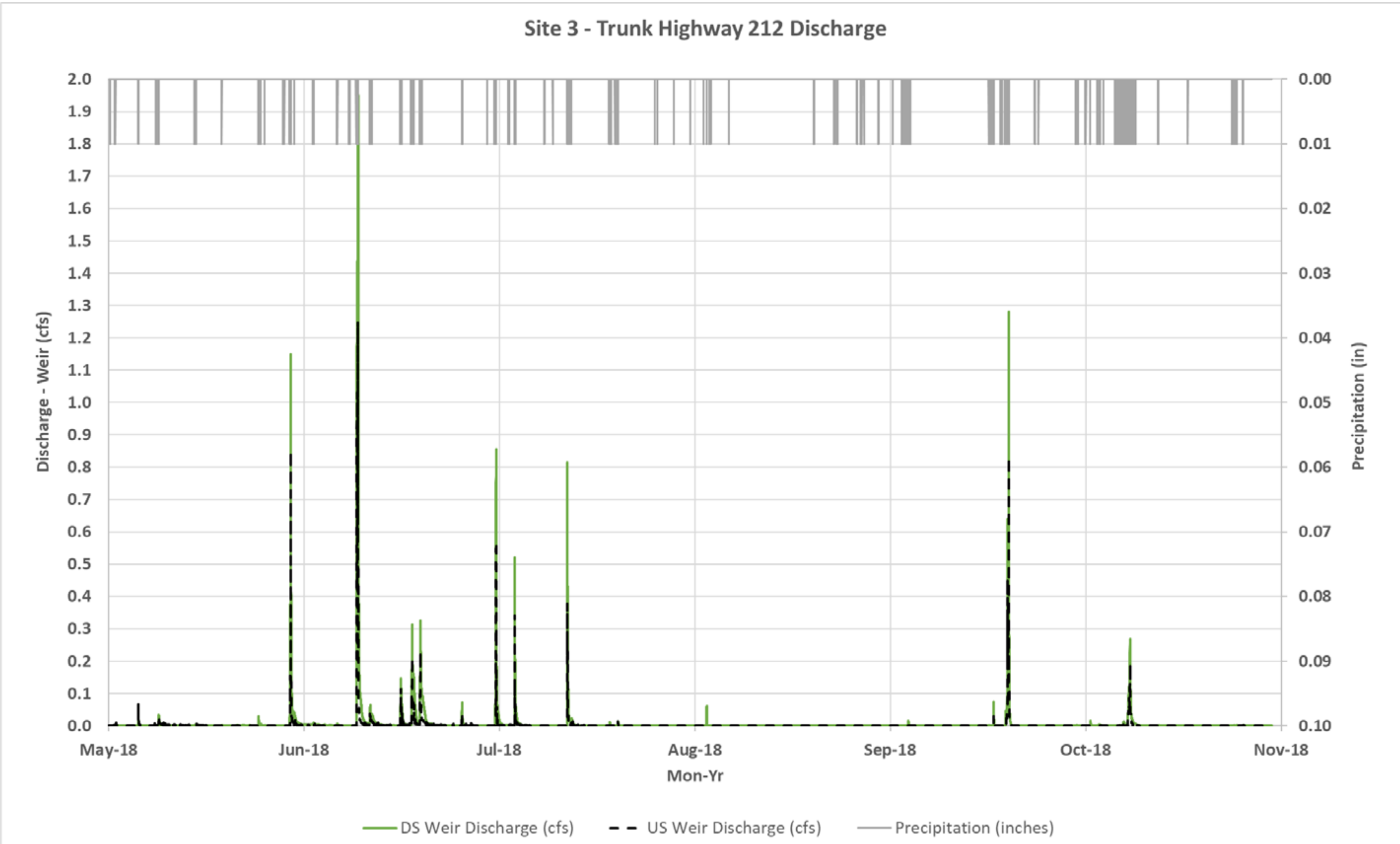


Figure 3-2. Difference Between Inflow and Outflow, May- October

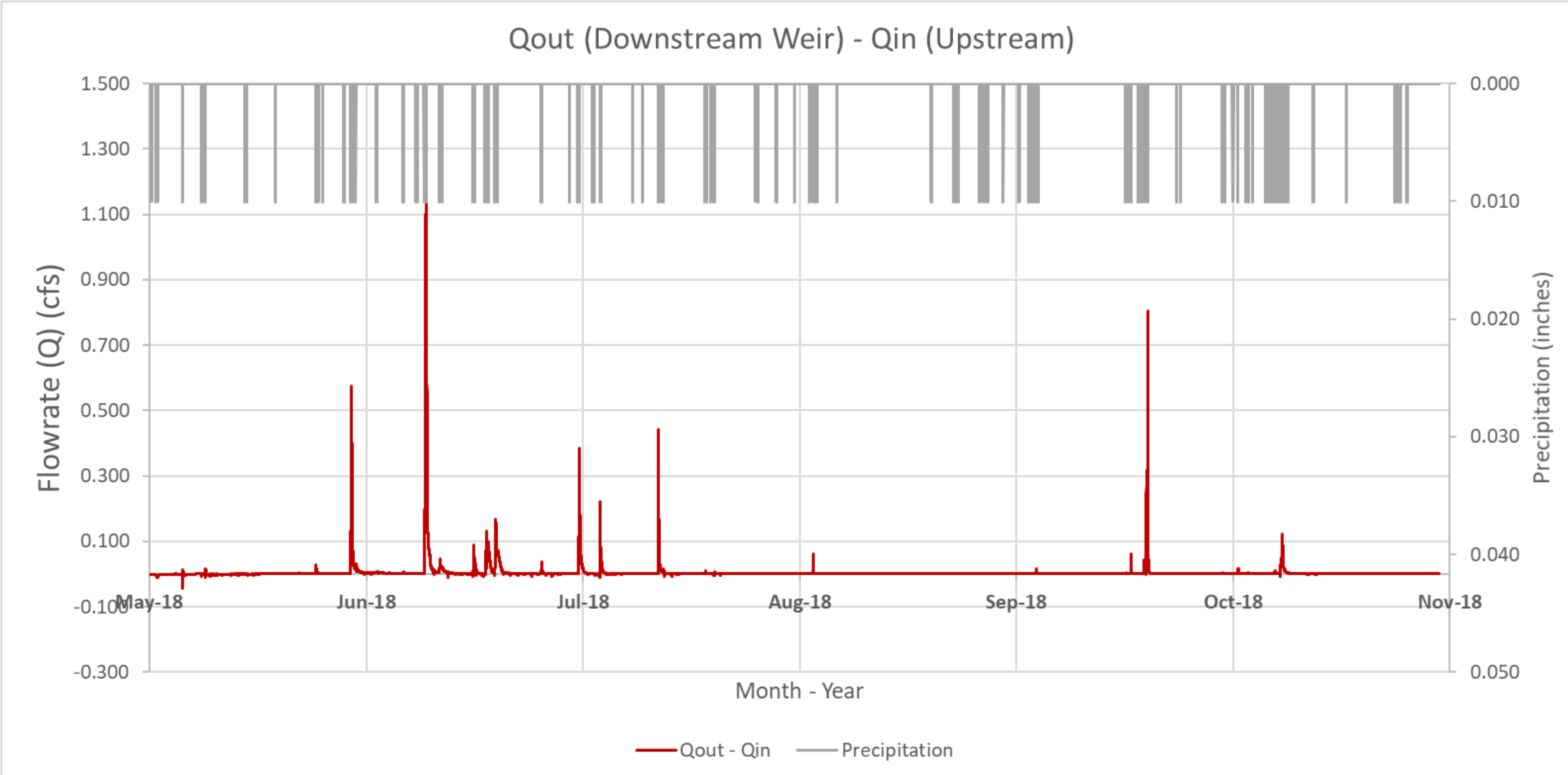
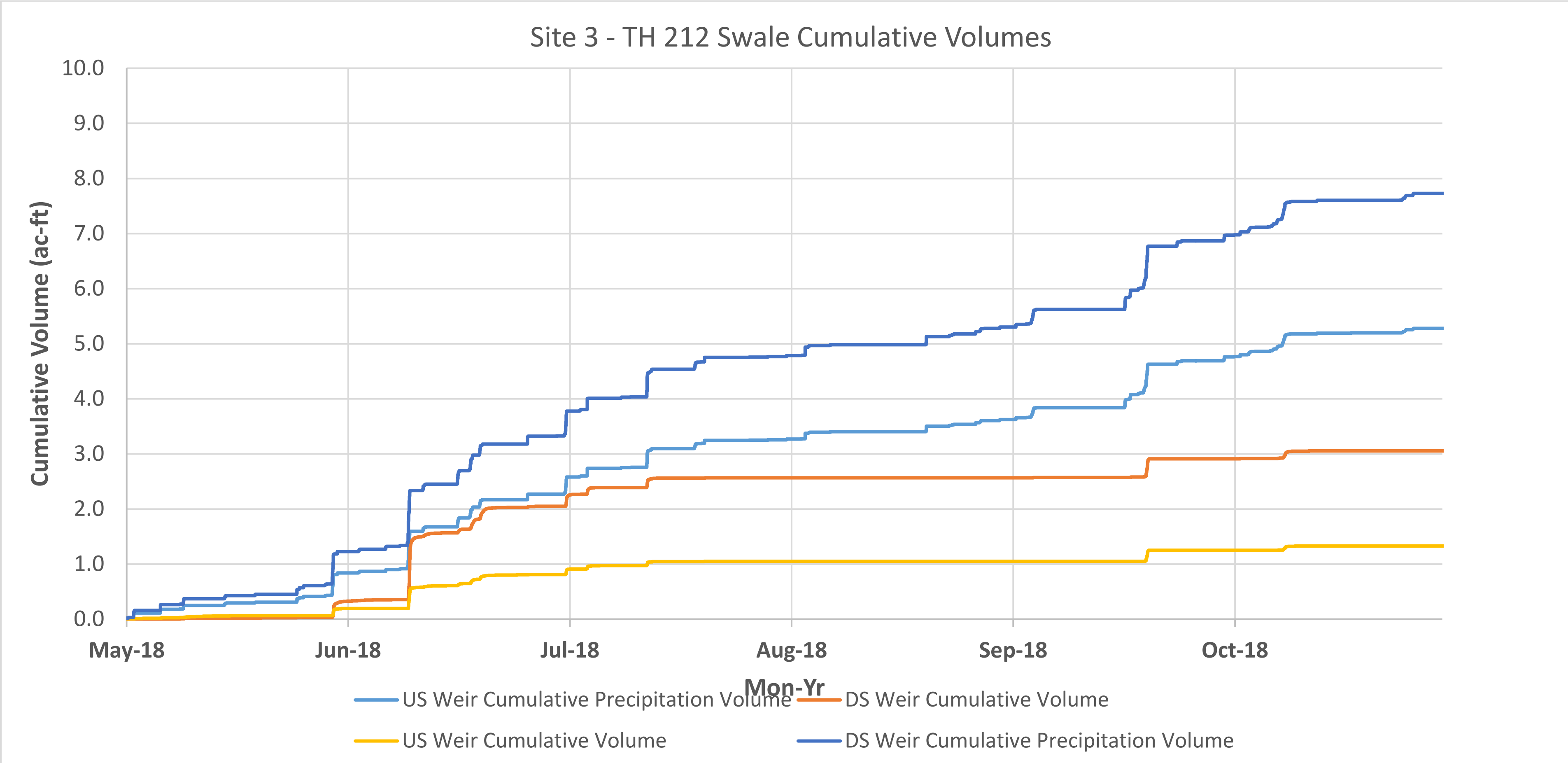


Figure 3-3. Cumulative Discharge Volume, April-October



Type	Date Range		Volume Analysis (ac-ft)							
			US Weir	WS Area (acres)	2.4	Date Range		DS Weir	WS Area (acres)	3.4
	Start Date	End Date	Weir Volume	Precipitation Volume	Fraction	Start Date	End Date	Weir Volume	Precipitation Volume	Fraction
Full Data Record	4/28/2018	11/1/2018	1.33	5.28	25.2%	5/1/2018	11/1/2018	3.06	7.73	39.5%

Figure 3-4. Site 3- Trunk Highway 212 Swale Discharge Hydrograph (May – November)

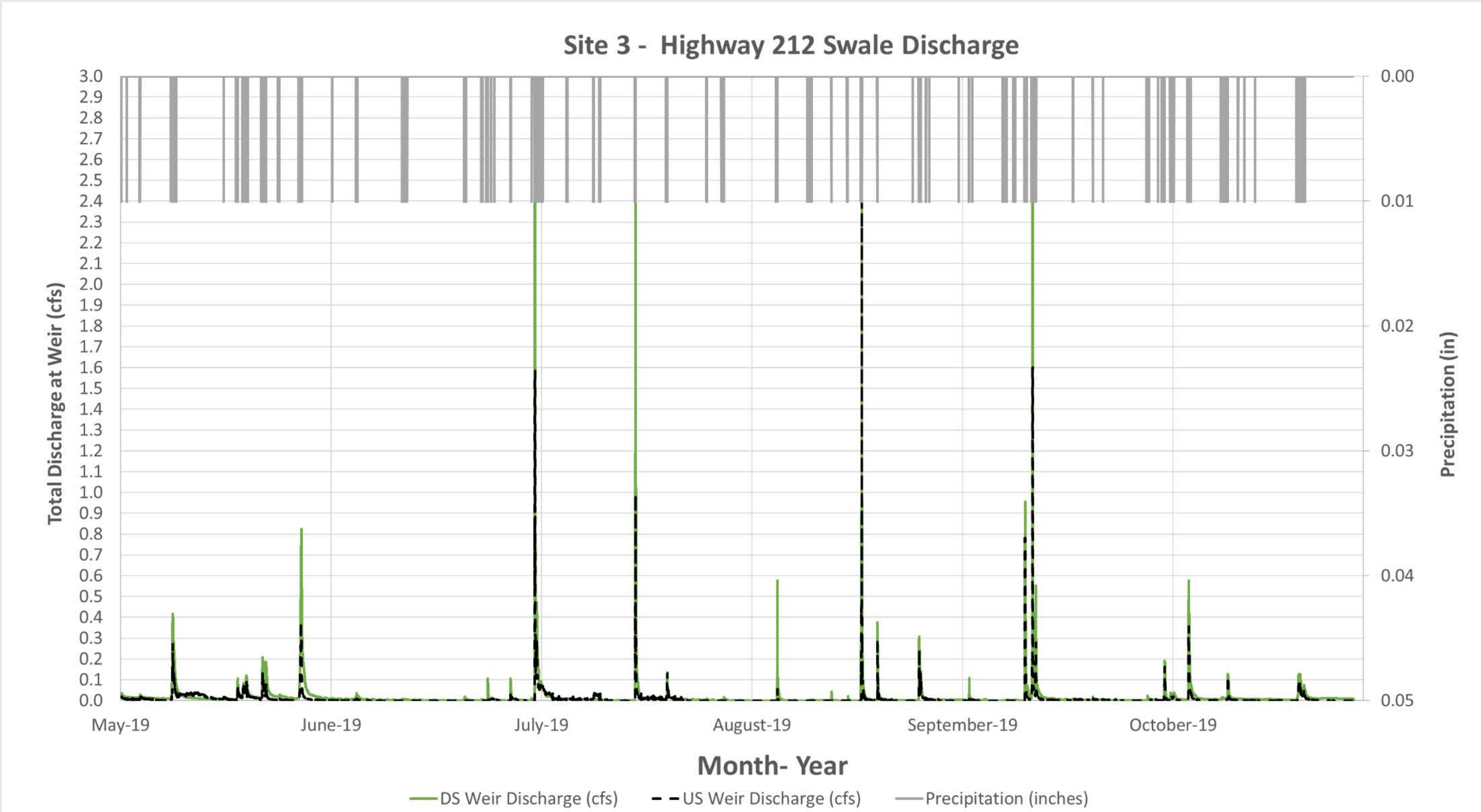


Figure 3-5. Swale Inflow minus Outflow, Site 3 May-October

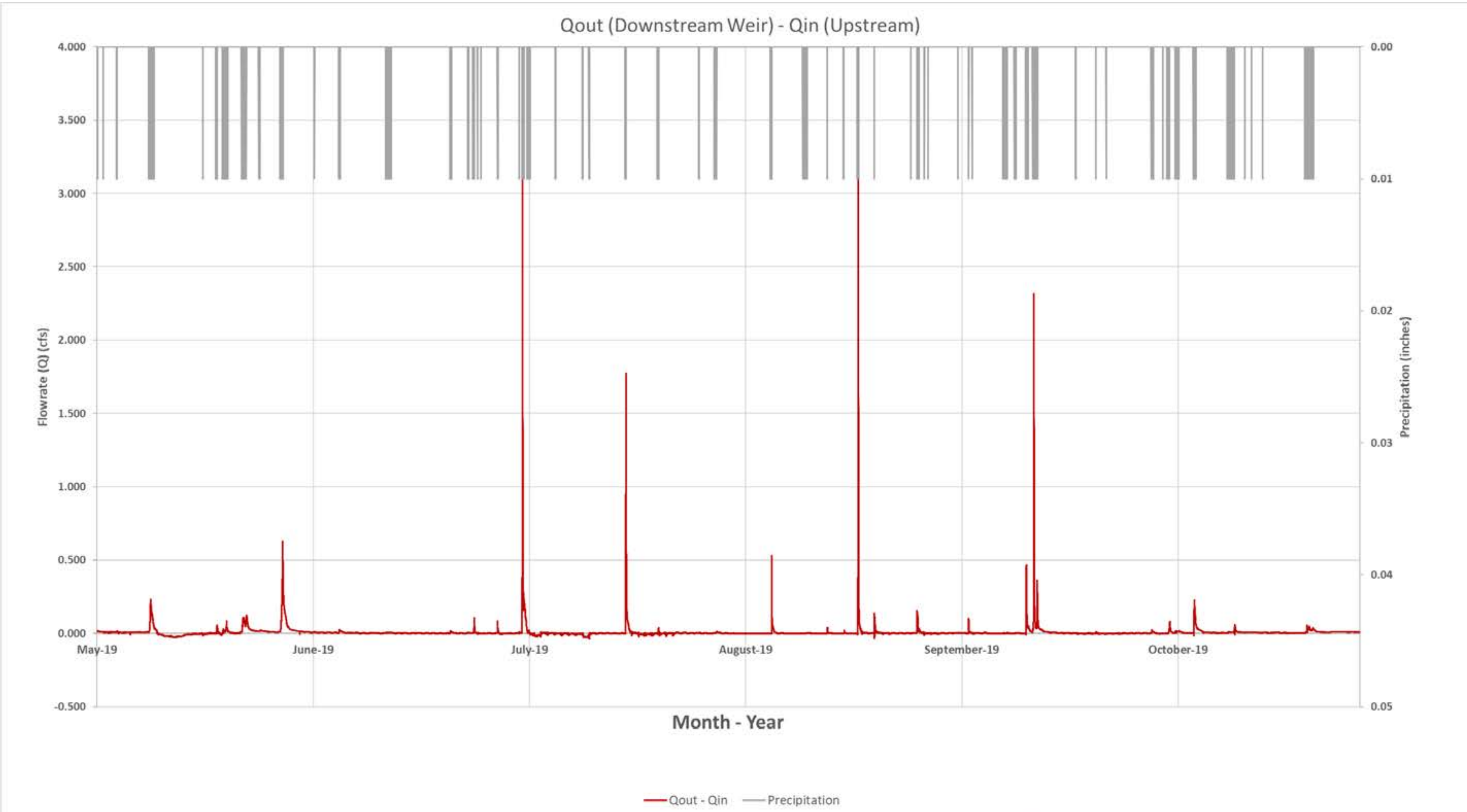
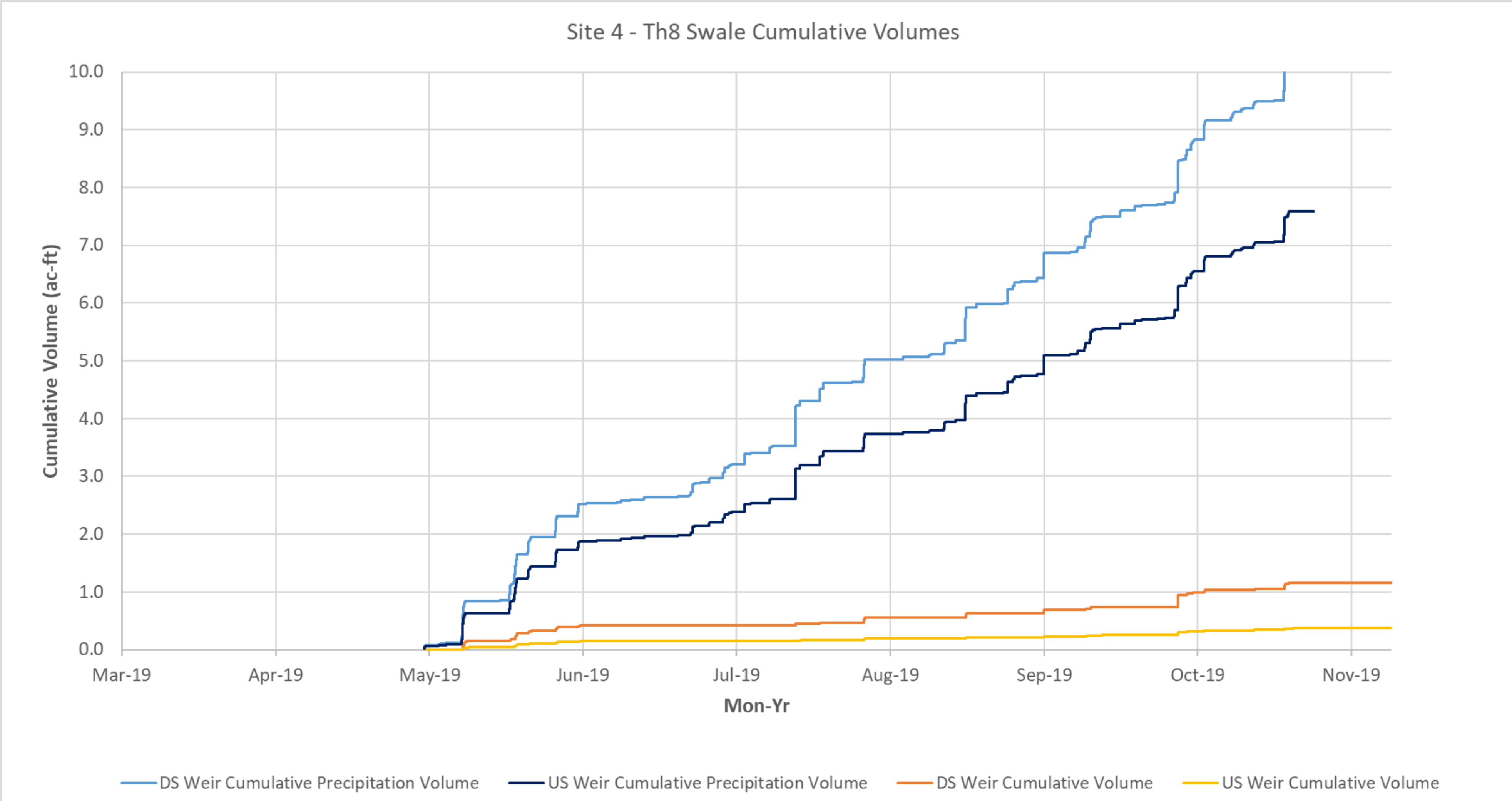


Figure 3-6. Cumulative volume of Weir discharge and precipitation May-Nov



			Volume Analysis (ac-ft)								
	Date Range		US Weir	WS Area (acres)	2.3	Date Range		DS Weir	WS Area (acres)	3.4
Type	Start Date	End Date	Weir Volume	ecipitation Volume (ac-f	Fraction	Start Date	End Date	Weir Volume	ecipitation Volume (ac-f	Fraction
Full Data Record	5/1/2019	10/29/2019	3.36	5.16	65.1%	5/1/2019	10/29/2019	6.93	7.55	91.8%

Figure 3-7. Site 4 - Trunk Highway 8 Swale Discharge Hydrograph

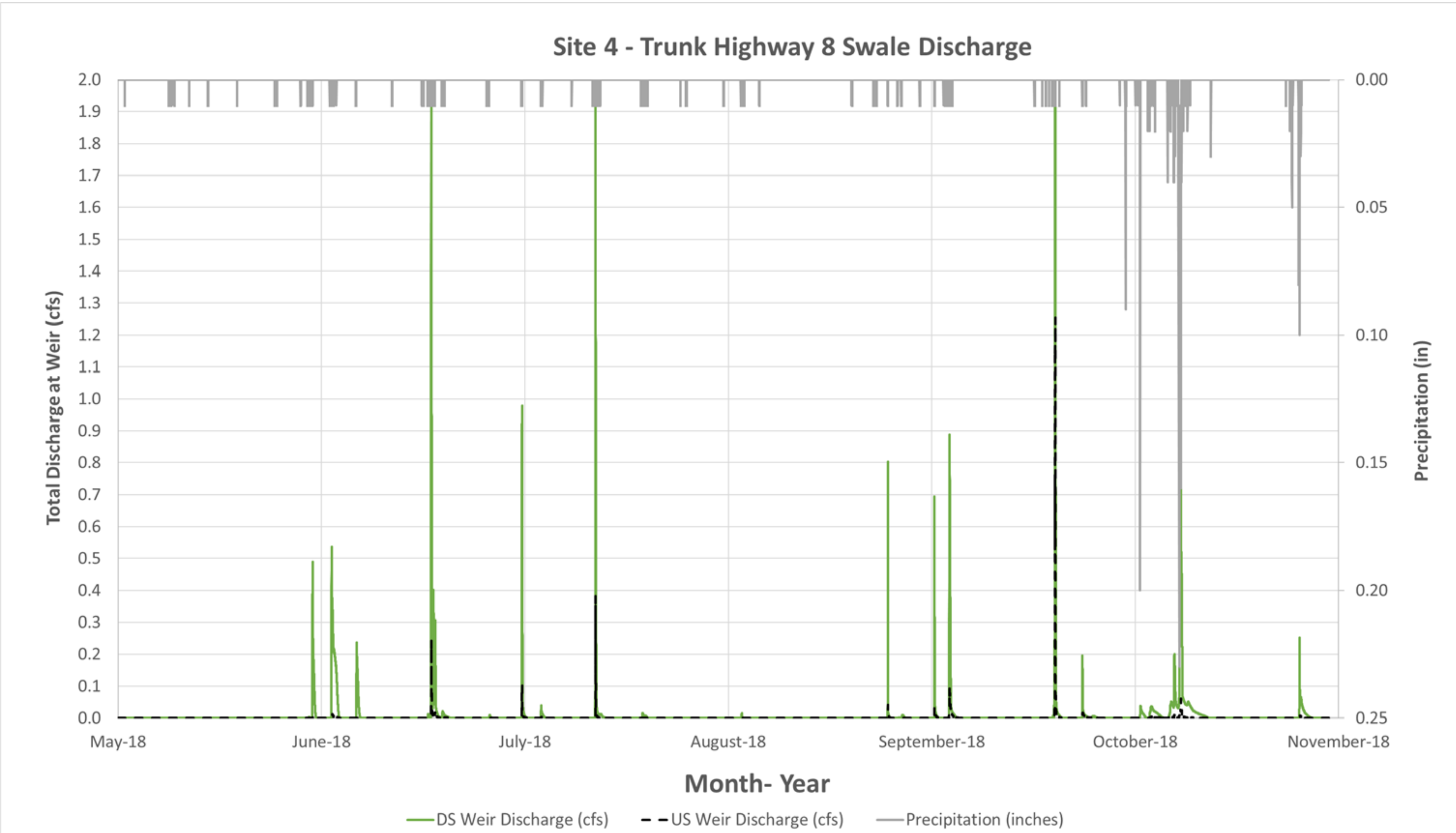


Figure 3-8. Swale Inflow minus Outflow, Site 4

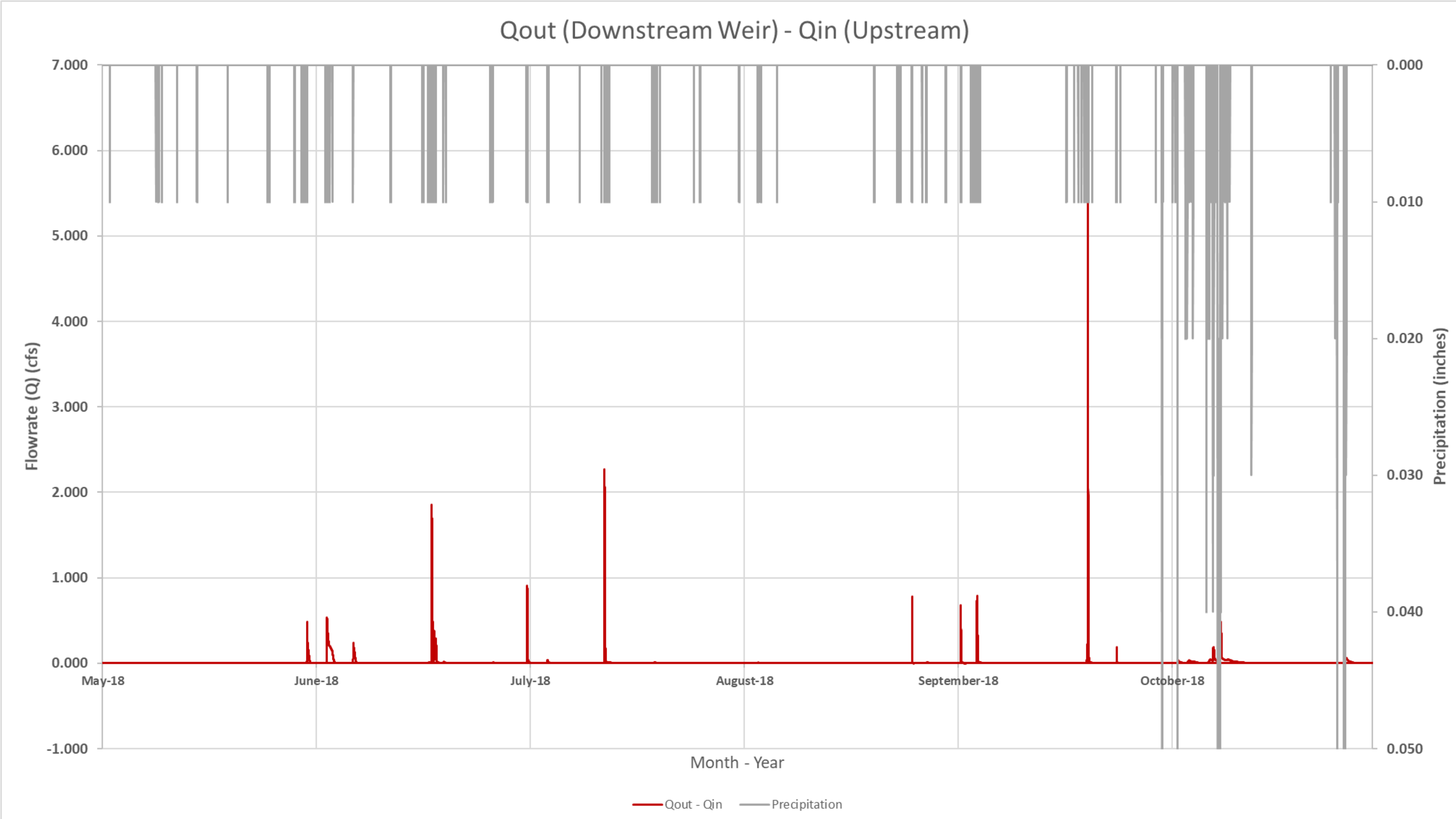
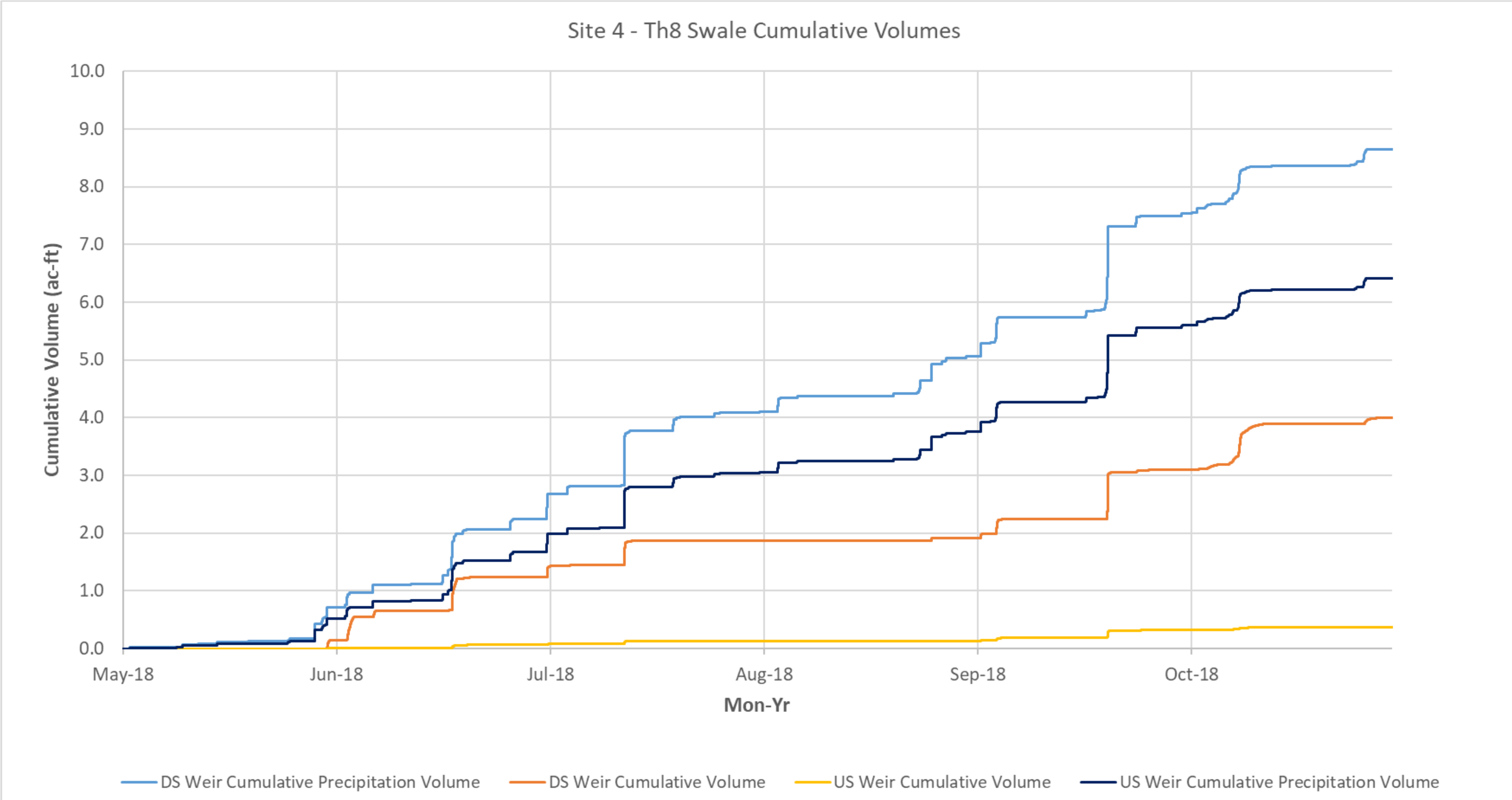


Figure 3-9. Cumulative volume of Weir discharge and precipitation



			Volume Analysis (ac-ft)							
	Date Range		US Weir	WS Area (acres)	3.3	Date Range		DS Weir	WS Area (acres)	4.4
Type	Start Date	End Date	Weir Volume	ecipitation Volume (ac-	Fraction	Start Date	End Date	Weir Volume	ecipitation Volume (ac-	Fraction
Full Data Record	5/1/2018	11/1/2018	0.37	6.42	5.7%	5/1/2018	11/1/2018	3.99	8.64	46.2%

Figure 3-10. Site 4 - Trunk Highway 8 Swale Discharge Hydrograph (May – November)

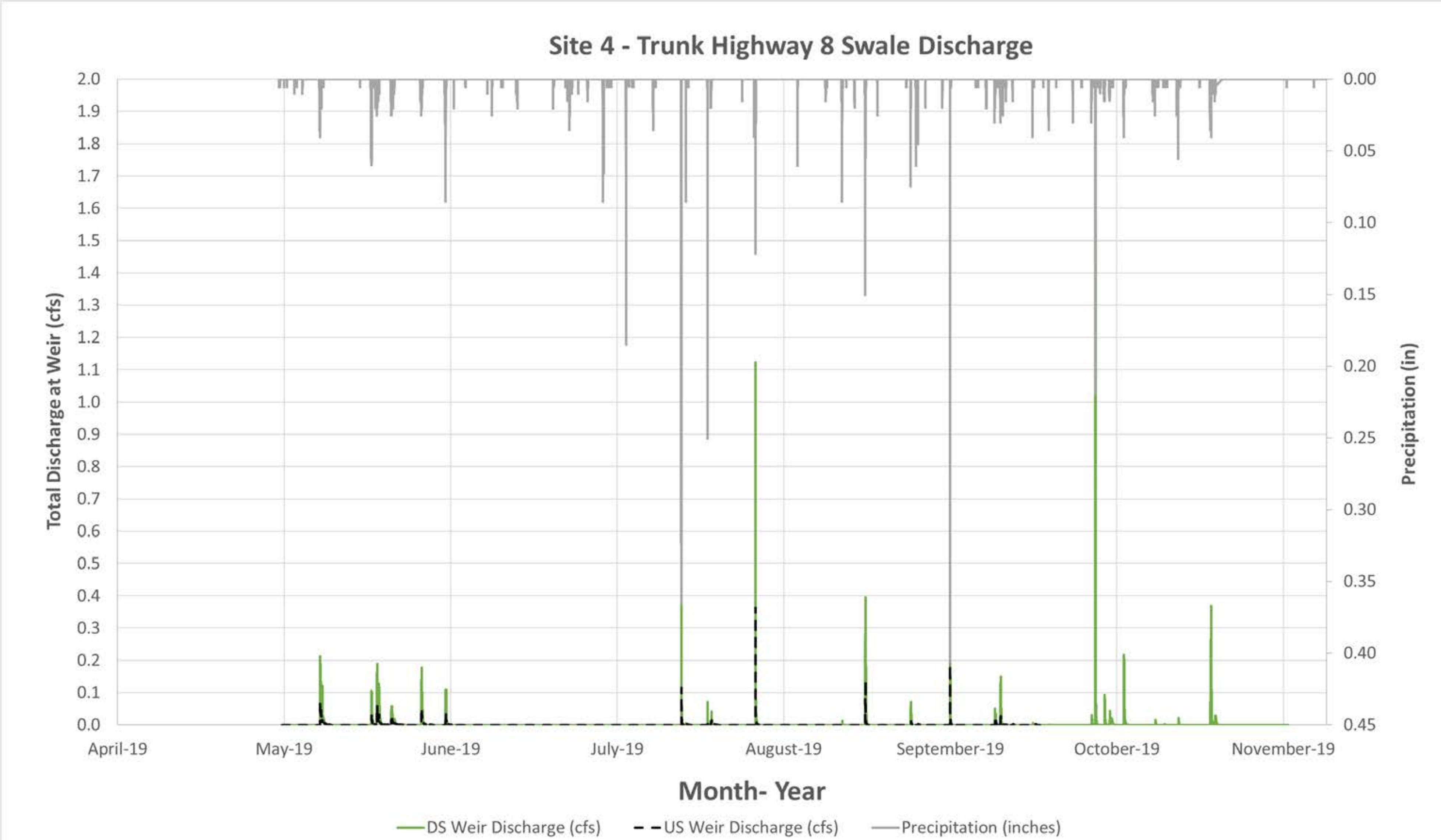


Figure 3-11. Swale Inflow minus Outflow, Site 4 May-Nov

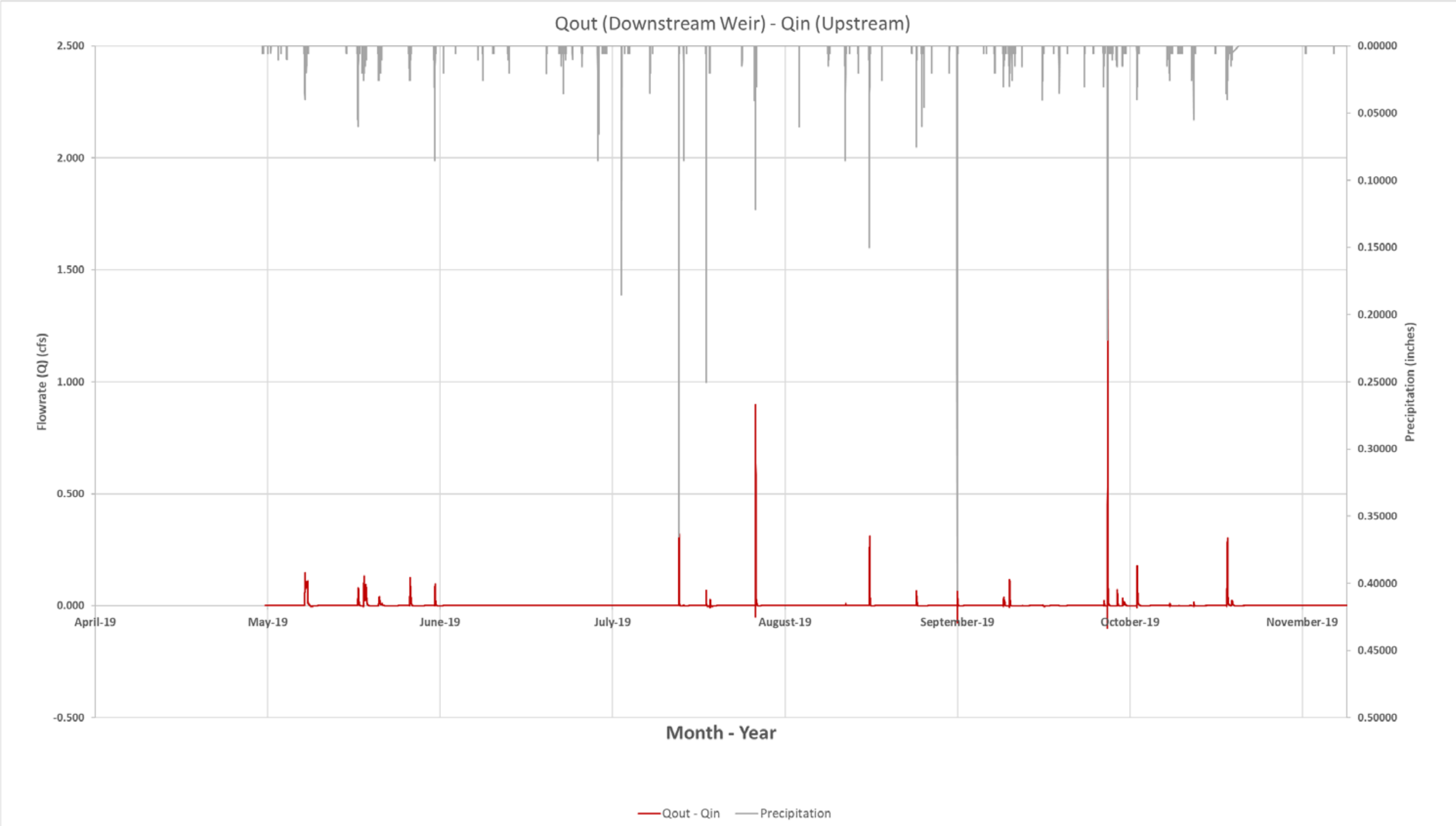
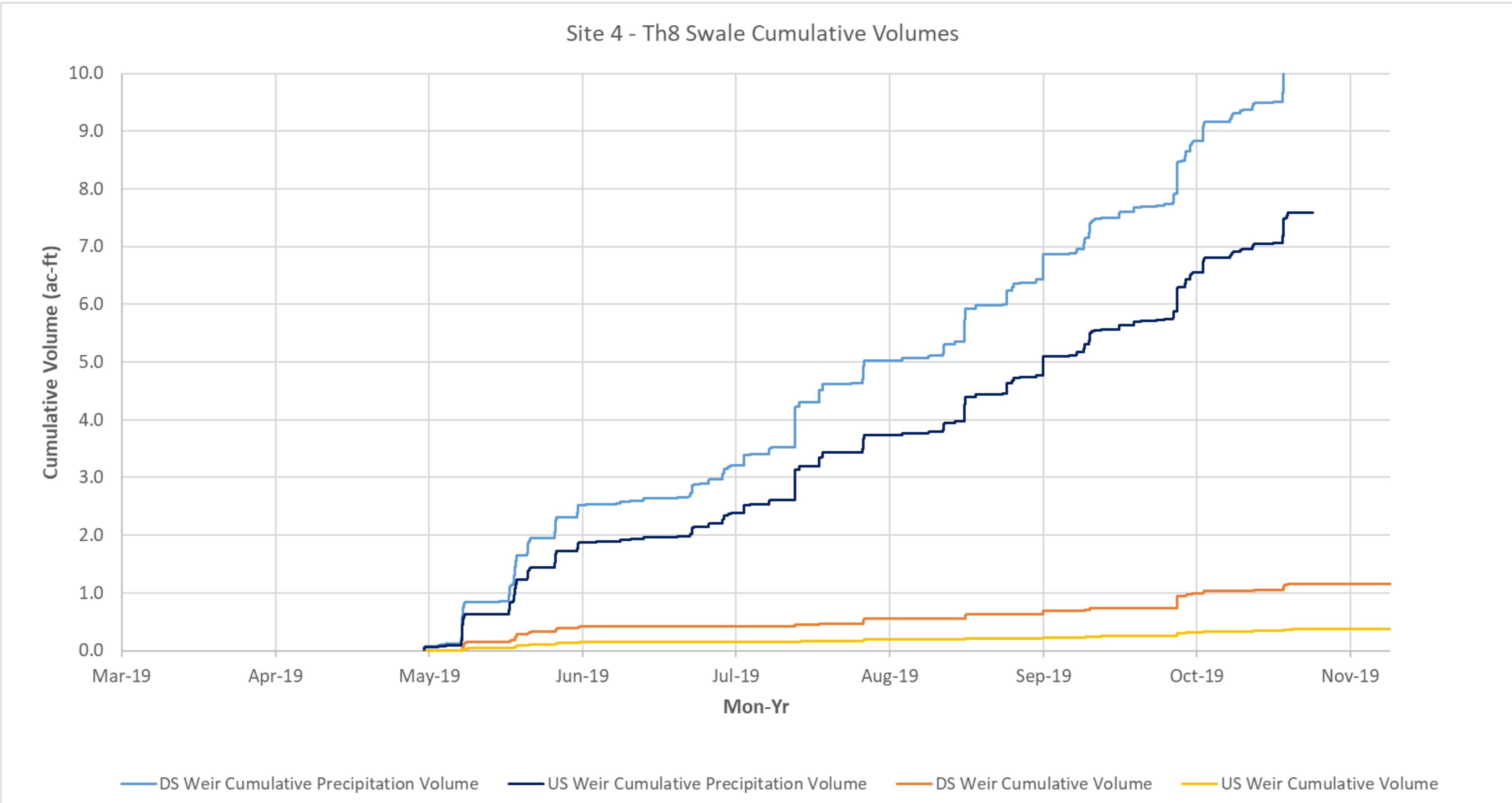


Figure 3-12. Cumulative volume of Weir discharge and precipitation May-Nov



			Volume Analysis (ac-ft)							
	Date Range		US Weir	WS Area (acres)	3.3	Date Range		DS Weir	WS Area (acres)	4.4
Type	**Start Date**	**End Date**	**Weir Volume**	**ecipitation Volume (ac-**	**Fraction**	**Start Date**	**End Date**	**Weir Volume**	**ecipitation Volume (ac-**	**Fraction**
Full Data Record	5/1/2019	11/12/2019	0.37	7.58	4.9%	5/1/2019	11/12/2019	1.15	10.20	11.3%

4.0 Modeling

XP-SWMM was chosen to model the rainfall runoff generation and soil infiltration aspects of each impervious and pervious land segment tributary to each swale section studied. XP-SWMM accounts for all of the necessary water balance processes to provide continuous simulation and context/comparison with the field monitoring results of this study. The only limitation of the XP-SWMM modeling is that it does not specifically account for groundwater flow, which for this application, would mean that it is unable to simulate interflow or the limiting effect that a seasonally high groundwater table would have on swale infiltration rates.

For this study, each XP-SWMM modeling scenario was set up to simultaneously simulate infiltration associated with Horton, Green-Ampt and SCS Curve Number methodologies, as well as infiltration from the main channel. The results of flow simulated for each modeling scenario allow for direct comparison to the monitoring data (discussed in Section 3) to evaluate whether there is one infiltration methodology that more-closely corresponds with the observed flows at each site. The infiltration input parameters set for each method were based on published rates or curve numbers associated with the hydrologic soil group(s) present within each drainage area.

4.1 XP-SWMM Inputs

The XP-SWMM modeling approach used in this study relied on distinguishing the individual impervious and pervious land segments, and associated flow paths, tributary to each swale to provide robust modeling of these systems. Figures 4-1 and 4-2 shows how each impervious and pervious land segment directly tributary to each weir was conceptualized and corresponded with the flow paths that allow for infiltration of runoff. For each study area, XP-SWMM was set up and modeled to ensure that flow from the impervious road segments (#1 in Figures 4-1 and 4-2) could be redirected to the adjacent pervious swale segment (#2 in Figures 4-1 and 4-2) and subject to the associated soil infiltration properties of that land segment before the flow proceeds downgradient along the bottom of the swale to the weir.

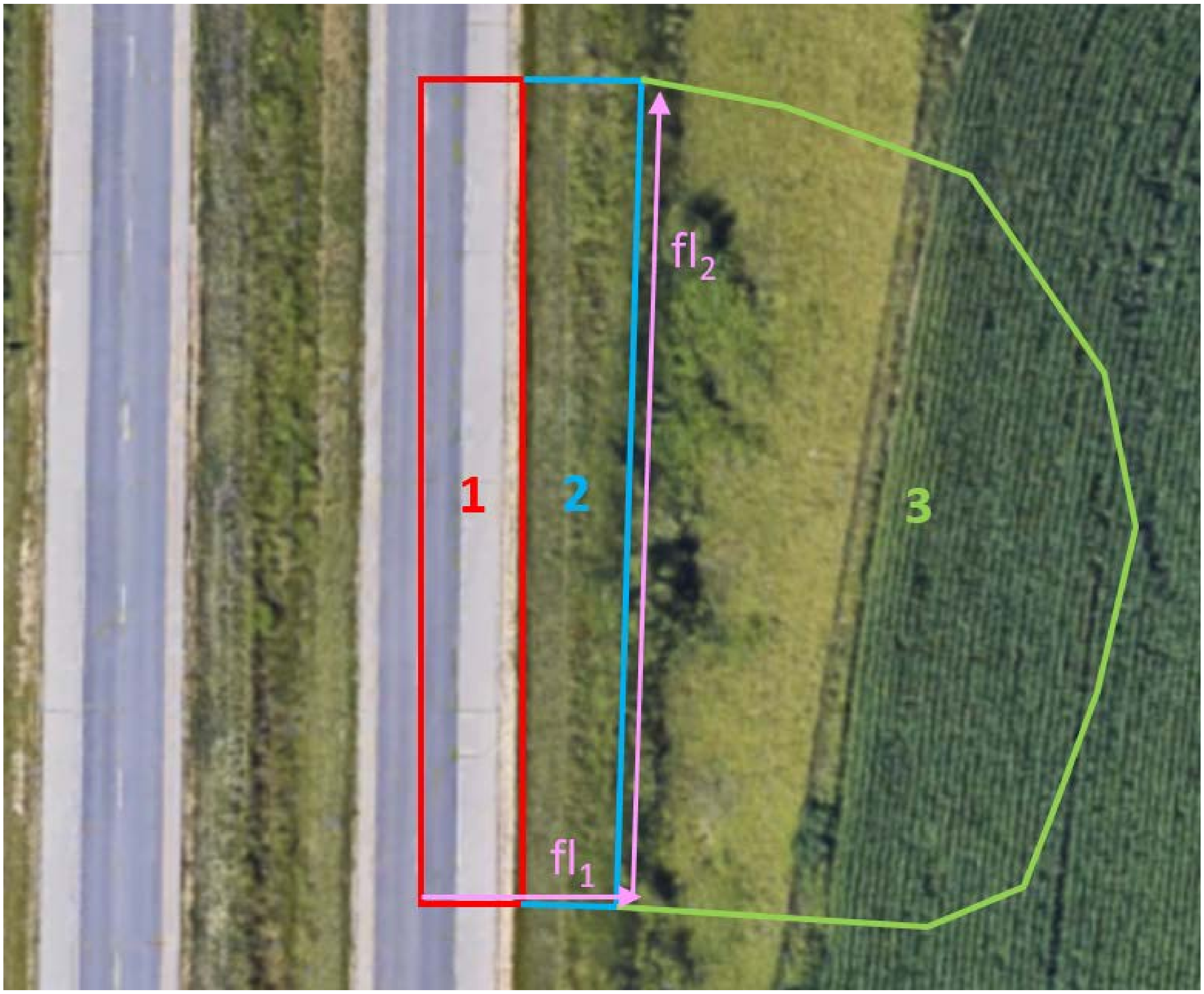


Figure 4-1 Plan view conceptualizing individual land segments modeled in XP-SWMM

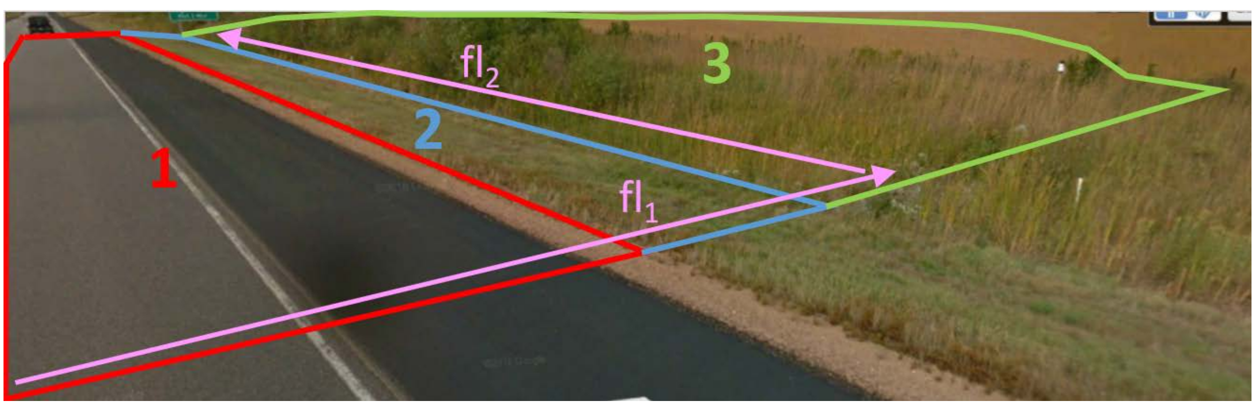


Figure 4-2 Cross-sectional view conceptualizing individual land segments modeled in XP-SWMM

4.2 XP-SWMM Water Balance Results

As previously discussed, continuous simulations with XP-SWMM account for all of the necessary water balance processes to provide continuous simulation and context/comparison with the field monitoring results of this study. For antecedent dry periods between each rainfall event simulated, XP-SWMM is regenerating the infiltration capacity of soils and/or simulating evaporation from depression storage areas. During each rainfall event, XP-SWMM is dynamically simulating changes to infiltration to determine how much of the excess rainfall will become surface runoff from pervious areas and simulating surface runoff from impervious areas when excess rainfall exceeds the available depression storage volume. In addition, accumulated flow within each swale conveyance can also be subject to infiltration (and tracked in the model results).

4.2.1 Site 3—TH212

Table 4-1 shows the respective water balance component overall results from the 2018 and 2019 model simulations at Site 3—TH212. Table 4-1 shows that the surface runoff volume represents between 7.9 and 14 percent of the rainfall volume each year.

Table 4-1 XP-SWMM simulated water balance component results (in inches) for Site 3—TH212

Year	Rainfall	Total Infiltration	Evaporation	Surface Runoff
2018	19.53	13.29	4.69	1.55
2019	26.32	20.65	1.89	3.78

4.2.2 Site 4—TH8

Table 4-2 shows the respective water balance component overall results from the 2018 and 2019 model simulations at Site 4—TH8. Table 4-2 shows that the surface runoff volume represents between 4.8 and 10 percent of the rainfall volume each year.

Table 4-2 XP-SWMM simulated water balance component results (in inches) for Site 4—TH8

Year	Rainfall	Total Infiltration	Evaporation	Surface Runoff
2018	17.60	12.81	3.95	0.84
2019	20.70	17.72	0.85	2.13

5.0 Monitoring/Modeling Comparison and Interpretation of Results

5.1 Site 3—TH212 Monitoring/Modeling Comparison

Figure 5-1 provides a plot of monitored and modeled cumulative flow volumes calculated for the upstream and downstream weirs at Site 3—TH212 for the SCS Curve Number infiltration methodology during 2018. There are no modeled results from 2019 for the SCS method at Site 3 because XP-SWMM could not reset the initial abstraction during a large event on August 17th.

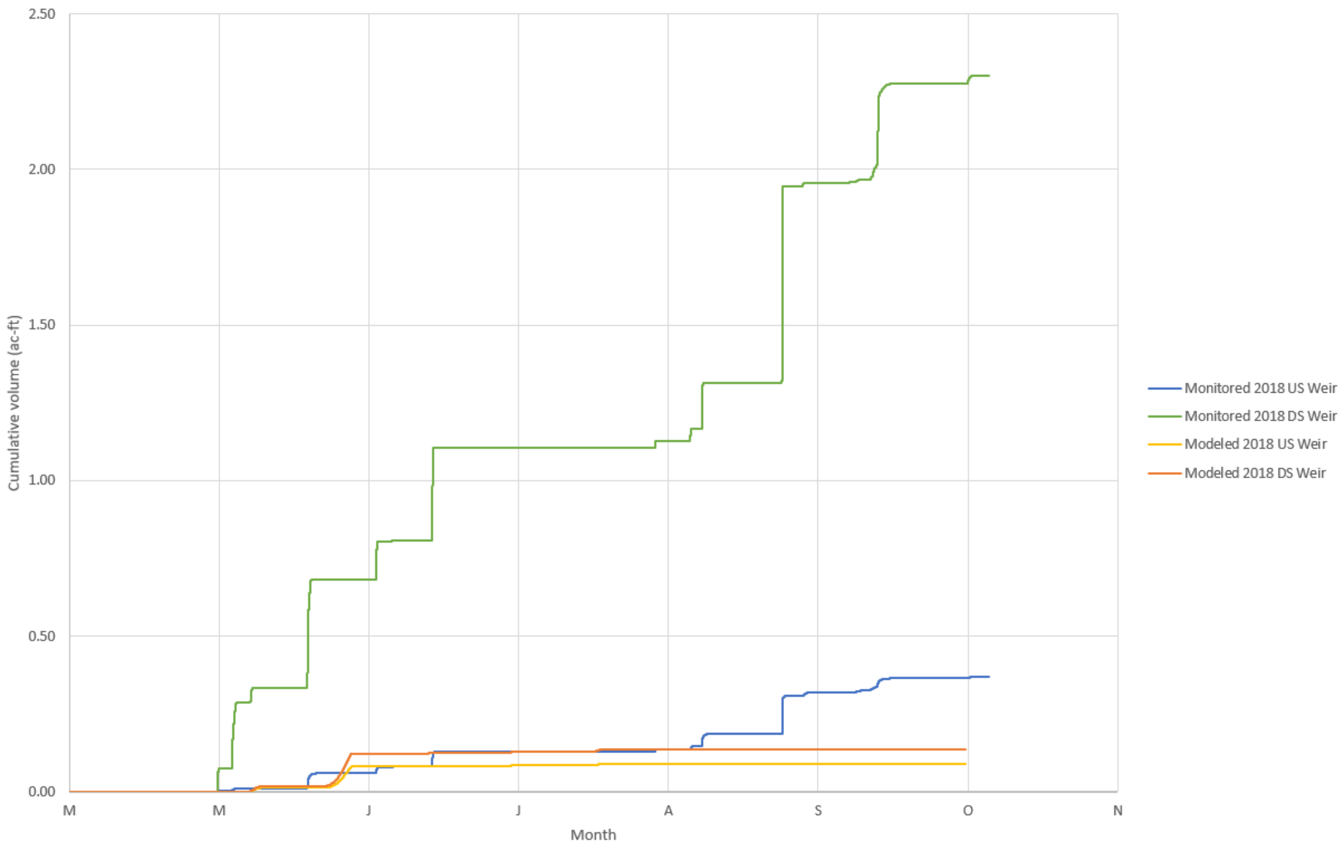


Figure 5-1 Monitored and Modeled Cumulative Flow Volumes from 2018 for SCS Methodology

Figures 5-2 and 5-3 provide plots of monitored and modeled cumulative flow volumes calculated for the upstream and downstream weirs at Site 3—TH212 for the Horton infiltration methodology during 2018 and 2019, respectively.

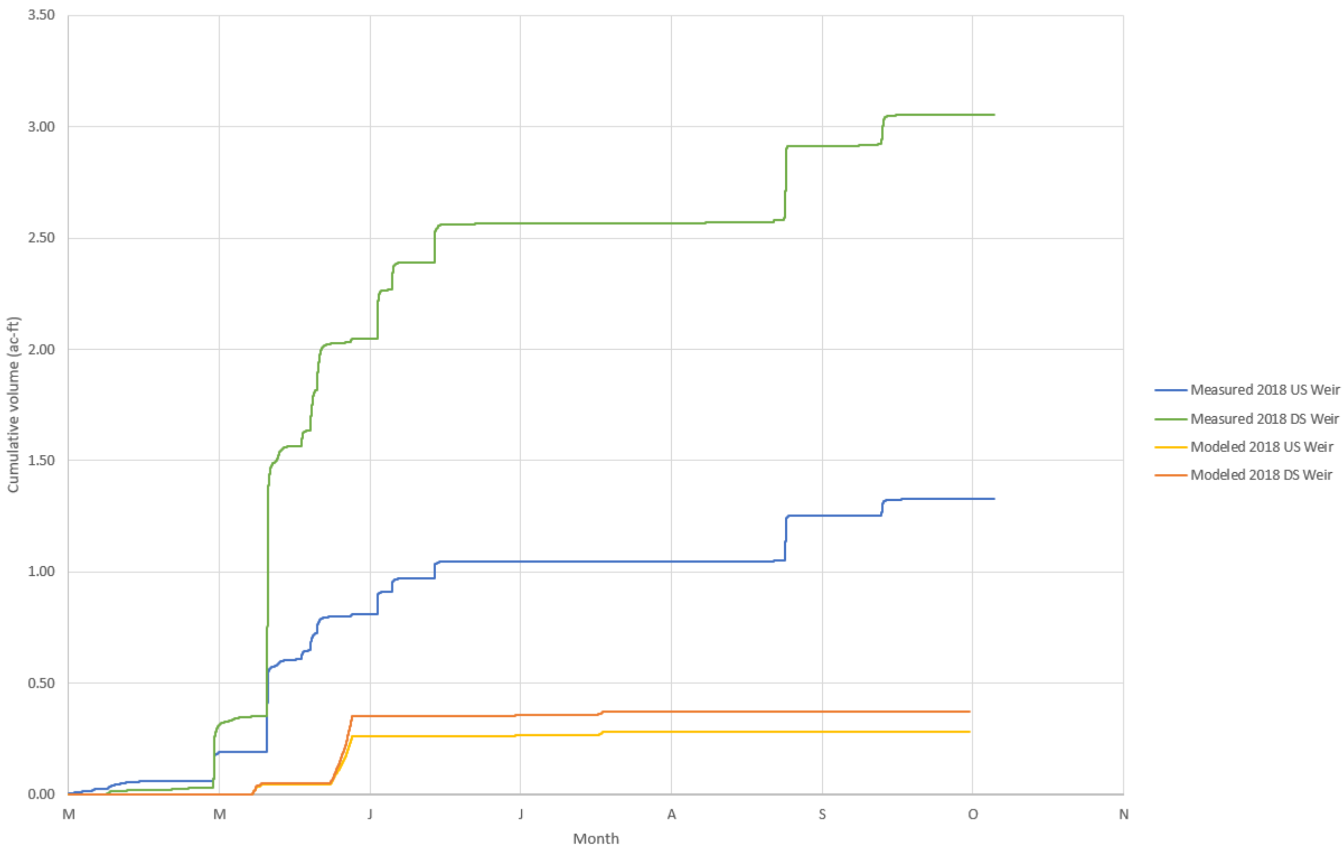


Figure 5-2 Monitored and Modeled Cumulative Flow Volumes from 2018 for Horton Methodology

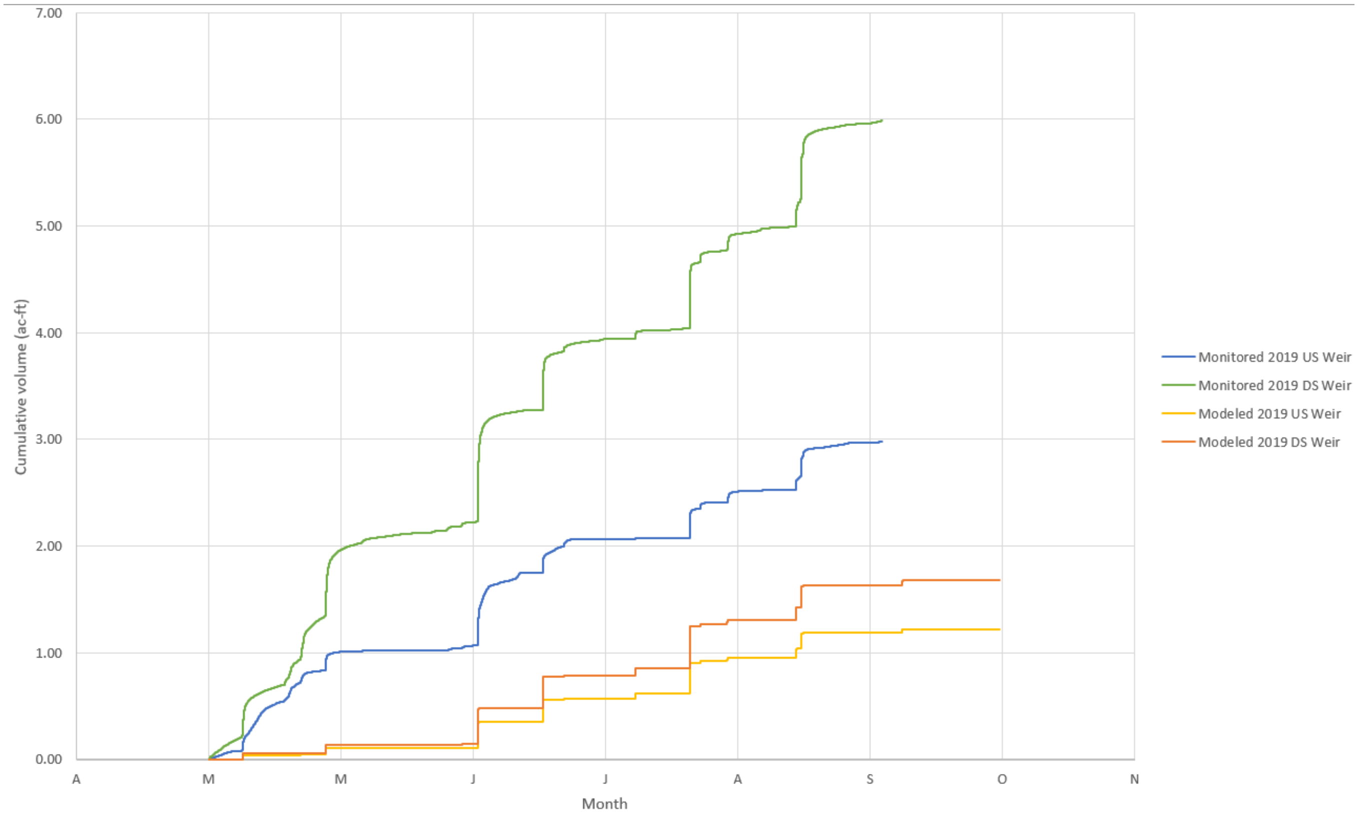


Figure 5-3 Monitored and Modeled Cumulative Flow Volumes from 2019 for Horton Methodology

Figure 5-4 provides a plot of monitored and modeled cumulative flow volumes calculated for the upstream and downstream weirs at Site 3—TH212 for the Green-Ampt infiltration methodology during 2019. The Green-Ampt infiltration methodology did not generate any surface runoff at Site 3 during the 2018 simulation.

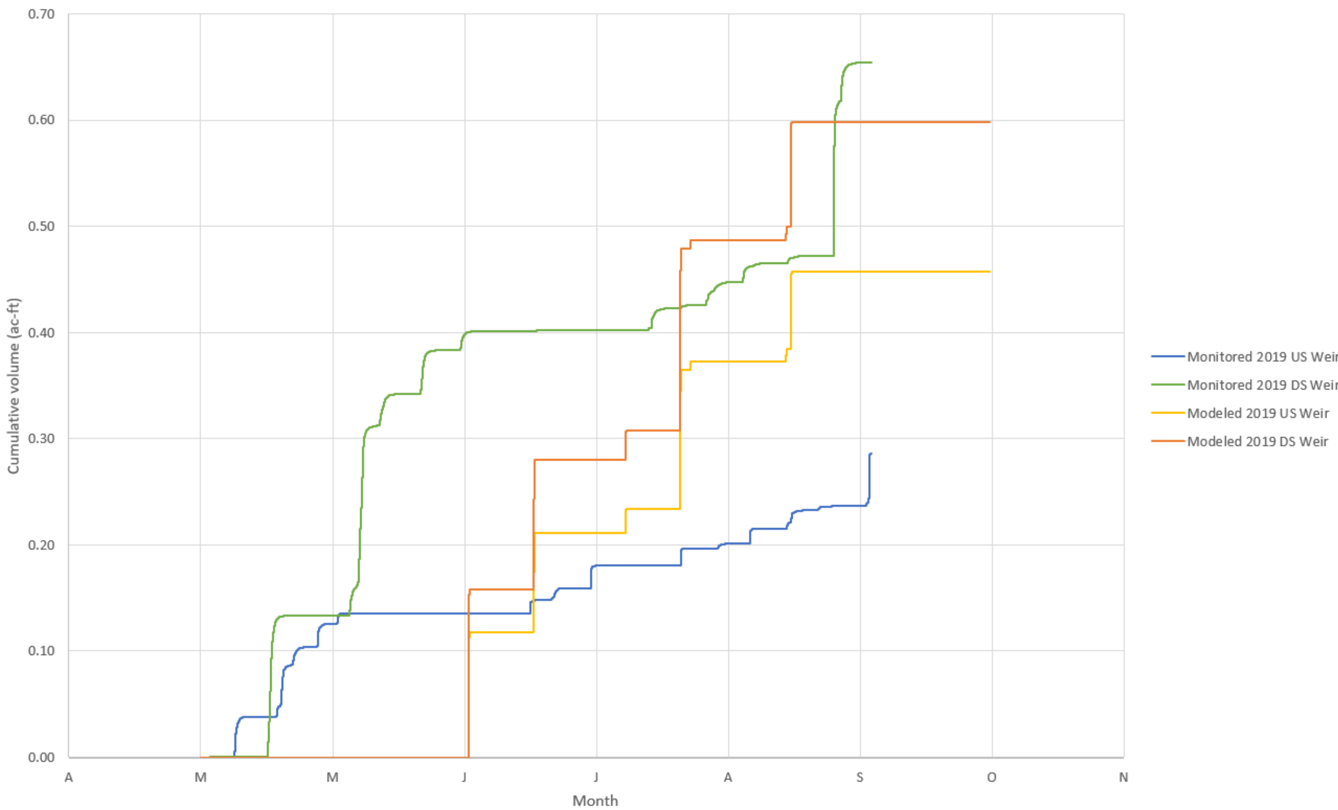


Figure 5-4 Monitored and Modeled Cumulative Flow Volumes from 2019 for Green-Ampt Methodology

5.2 Site 4—TH8 Monitoring/Modeling Comparison

Figures 5-5 and 5-6 provide plots of monitored and modeled cumulative flow volumes calculated for the upstream and downstream weirs at Site 4—TH8 for the SCS Curve Number infiltration methodology during 2018 and 2019, respectively.

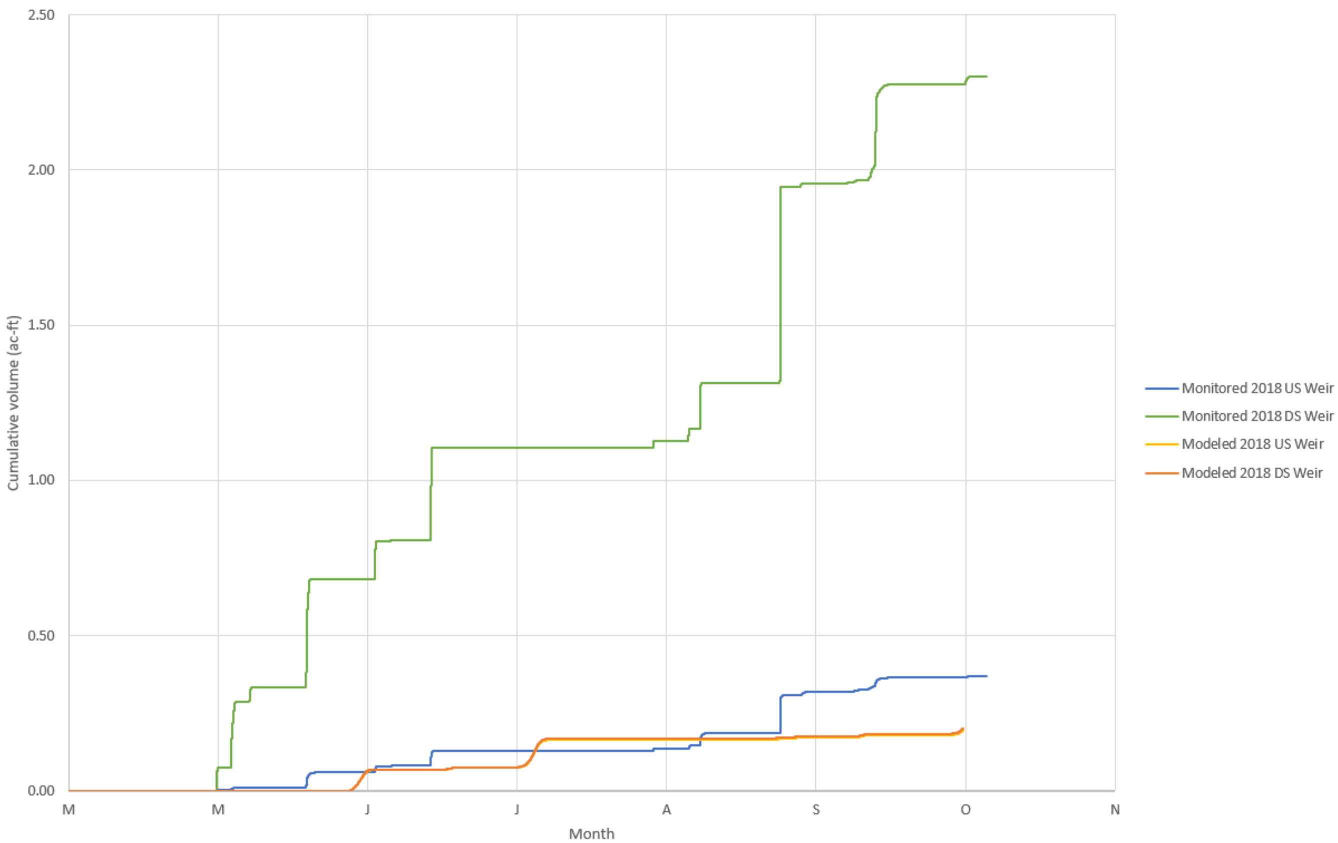


Figure 5-5 Monitored and Modeled Cumulative Flow Volumes from 2018 for SCS Methodology

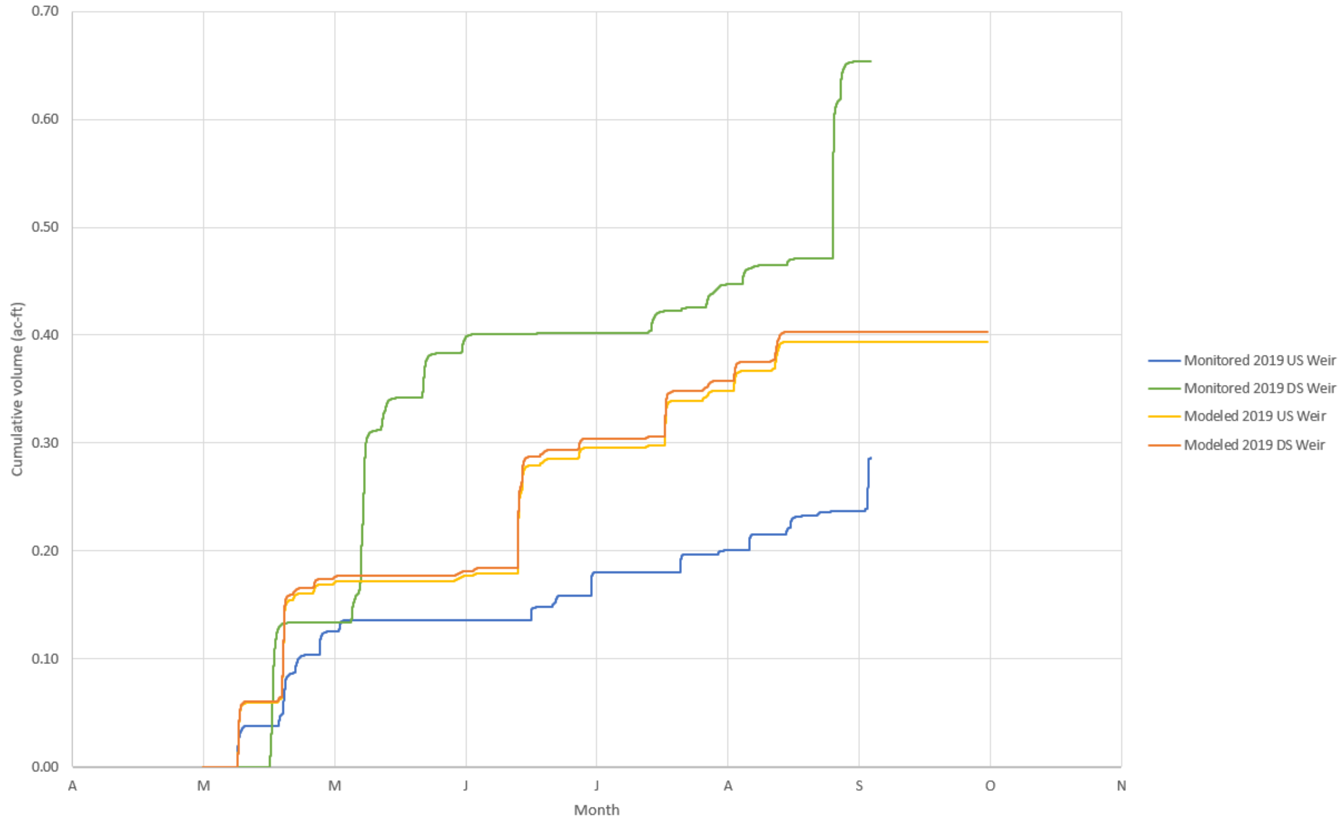


Figure 5-6 Monitored and Modeled Cumulative Flow Volumes from 2019 for SCS Methodology

Figures 5-7 and 5-8 provide plots of monitored and modeled cumulative flow volumes calculated for the upstream and downstream weirs at Site 4—TH8 for the Horton infiltration methodology during 2018 and 2019, respectively.

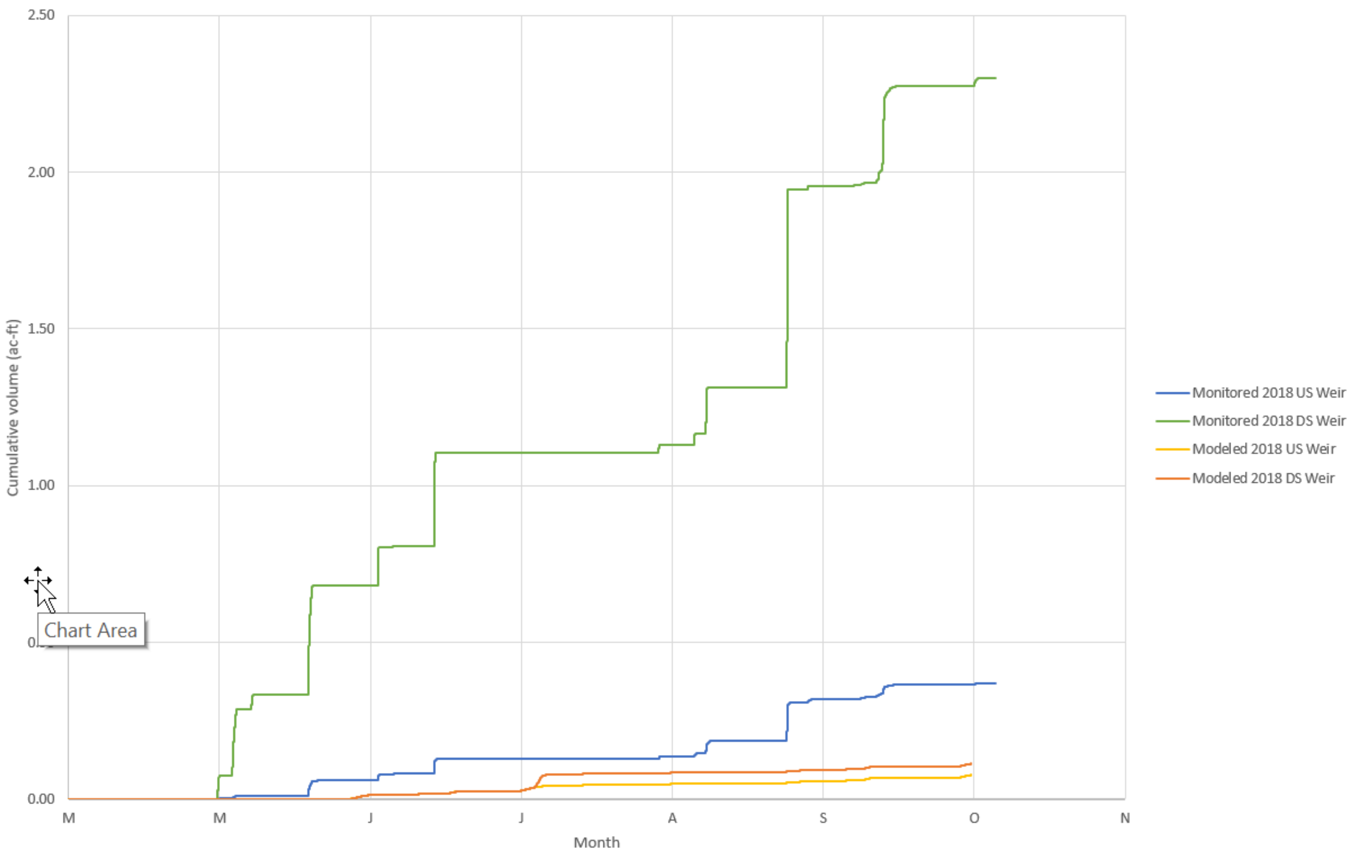


Figure 5-7 Monitored and Modeled Cumulative Flow Volumes from 2018 for Horton Methodology

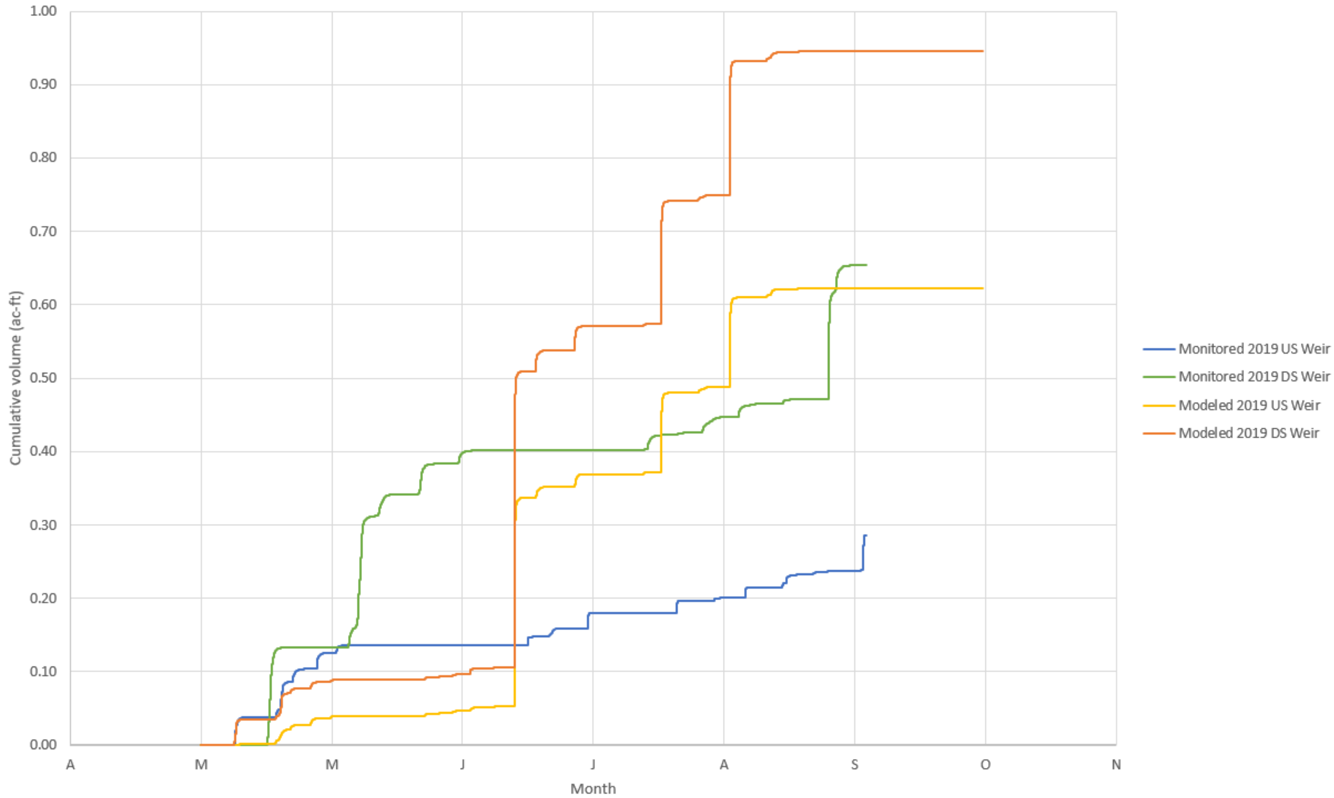


Figure 5-8 Monitored and Modeled Cumulative Flow Volumes from 2019 for Horton Methodology

Figures 5-9 and 5-10 provide plots of monitored and modeled cumulative flow volumes calculated for the upstream and downstream weirs at Site 4—TH8 for the Green-Ampt infiltration methodology during 2018 and 2019, respectively.

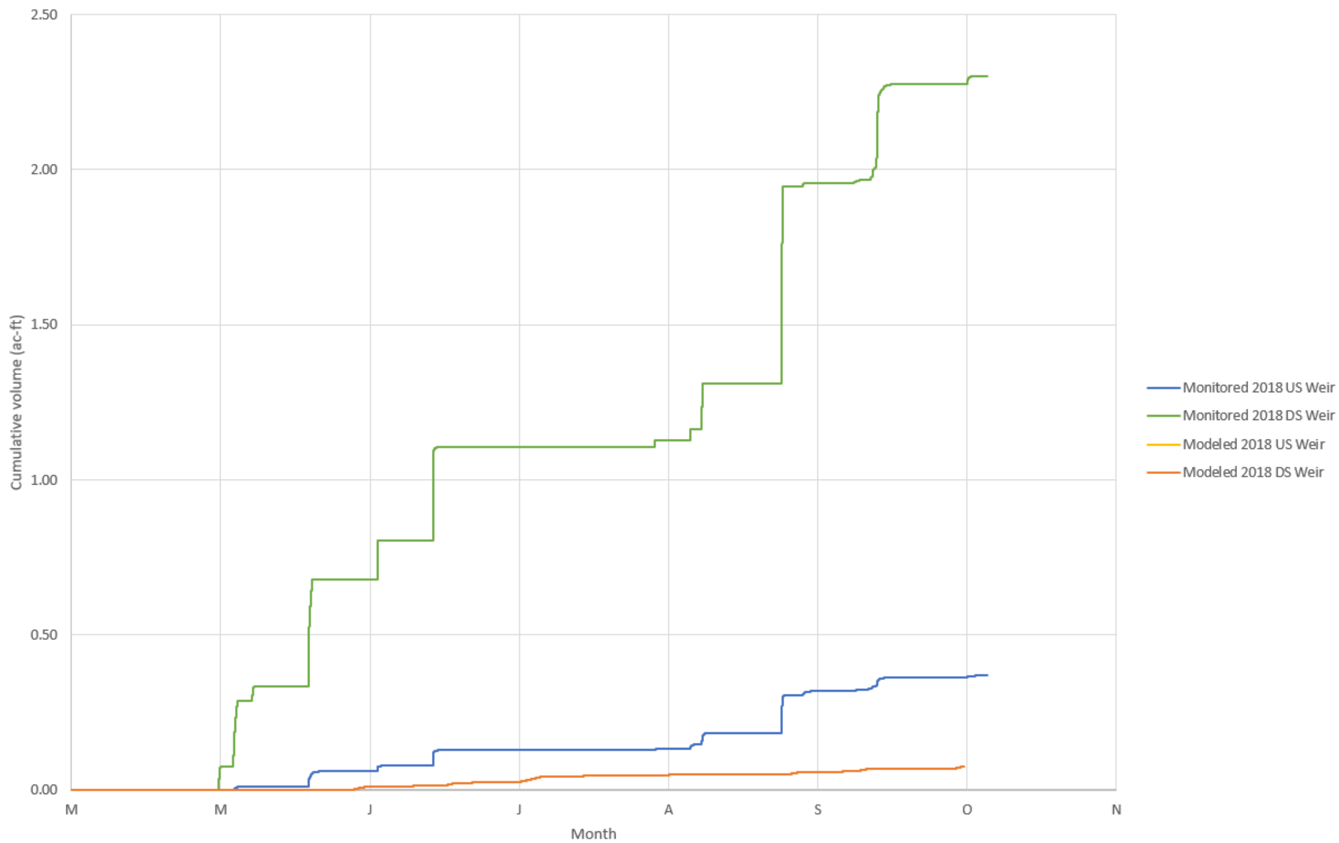


Figure 5-9 Monitored and Modeled Cumulative Flow Volumes from 2018 for Green-Ampt Methodology

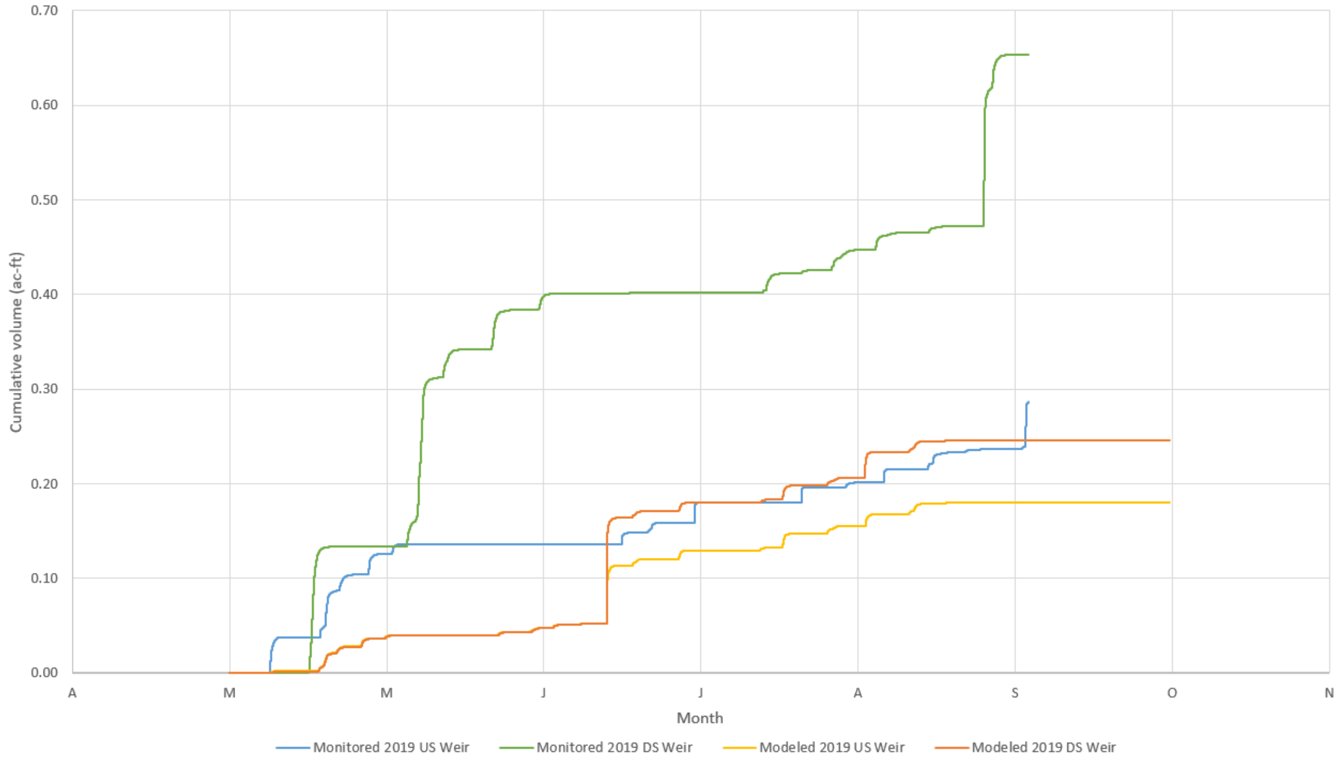


Figure 5-10 Monitored and Modeled Cumulative Flow Volumes from 2019 for Green-Ampt Methodology

5.3 Interpretation of Results

A detailed review of Figures 5-1 through 5-3, along with Figures 5-5, 5-7 and 5-9, indicate that all three infiltration methodologies resulted in modeled flows that are generally less than the monitored flows for Sites 3 and 4. This is significant because modeling at both sites was based on accepted (infiltration rate) values for HSG B soils that were applied for each of the respective infiltration methodologies. The infiltration rate assumptions applied to the respective methodologies were already significantly lower than the MPD infiltration rate estimates at each site, except for Transect 3 at TH212 which generally had an estimate of zero infiltration. Figures 5-6, 5-8 and 5-10 indicate that the 2019 simulation at Site 4 contained a significant rainfall event in the record near mid-June that must not have actually occurred at the site. Ignoring the Site 4 runoff response to the mid-June event in 2019 confirms the same conclusion about all three infiltration methodologies overestimating the amount of infiltration that is actually occurring in the monitored swales.

Figures 5-1 through 5-10 also confirm that the downstream weir at Sites 3 and 4 experienced significantly more flow (than the upstream weir) that can't easily be accounted for in the modeling since the incremental increase in drainage area at each site is much lower than observed increases in flow during

2018 and 2019. This effect combined with the tendency to overestimate infiltration rates (discussed above) has potential implications for the use of XP-SWMM and any other models or calculators that utilize estimated infiltration rates based on MPD measurements or HSG-related publications. Since almost all of these tools and models ignore groundwater effects it is likely that the associated performance calculations have a tendency to attach more volume reduction credit to swales than is warranted.